AGARD-CP-600 Vol. 2

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AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE

AGARD CONFERENCE PROCEEDINGS 600

Future Aerospace Technology in the Service of the Alliance

(les Technologies aéronautiques et spatiales du futur au service de l'Alliance atlantique)

Volume 2:

Mission Systems Technologies

(les Technologies des systèmes de conduite de mission)

Unclassified papers presented at the AGARD Symposium held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997.

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The other volumes contain:

Volume 1:
Affordable Combat Aircraft
(le Coût de possession des avions de combat)
and
Plenary Sessions:
Future Directions in Aerospace Systems
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Future NATO Trends and Mission Scenarios
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(Interactions homme-machine du futur)

Volume 3:
Sustained Hypersonic Flight
(le Vol en croisière hypersonique)

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North Atlantic Treaty Organization
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The Mission of AGARD

According to its Charter, the mission of AGARD is to bring together the leading personalities of the NATO nations in the fields of science and technology relating to aerospace for the following purposes:

— Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community;

— Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);

— Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;

— Improving the co-operation among member nations in aerospace research and development;

— Exchange of scientific and technical information;

— Providing assistance to member nations for the purpose of increasing their scientific and technical potential;

— Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field.

The highest authority within AGARD is the National Delegates Board consisting of officially appointed senior representatives from each member nation. The mission of AGARD is carried out through the Panels which are composed of experts appointed by the National Delegates, the Consultant and Exchange Programme and the Aerospace Applications Studies Programme. The results of AGARD work are reported to the member nations and the NATO Authorities through the AGARD series of publications of which this is one.

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Mission Systems Technologies

(AGARD CP-600 Vol. 2)

Executive Summary

Advances in sensing and information processing/distribution technologies will enable highly innovative system concepts for achieving unprecedented improvements in military mission capabilities.

Assessing those major technology advances, the symposium was structured in five sessions hosting twenty four papers:

-1- **Mission management concepts**, introducing the subject, presenting technological requirements and giving as an example the unmanned tactical aircraft;

-2- **Sensors and electronic warfare**, showing how emerging Radio Frequency and Electro-Optics technologies are able to offer improved situational awareness, but may also defeat apparently reliable weapons;

-3- **Information and communications systems**, stressing the effective blending most likely to occur between market driven and specific military developments, as well as the need to account for the battlespace environment;

-4- **Information fusion and mission systems integration**, demonstrating among others how data fusion which is required for matching the information rate to the human, will result in drastically improving its accuracy and reliability;

-5- **System simulation**, emphasizing the major role of simulation technologies for cost-effective design of new military systems, evaluation of existing ones, training of operators, and paving the way to the concept of synthetic environments.

Based on emerging and rapidly evolving technologies, the presenters built a vision of future weapon systems capable of operating in a diverse range of hostile environments, under all weather conditions, and during day or night. Furthermore, autonomous situation appreciation capability, reliable communication channels and real-time decision aids were discussed, which will drastically reduce the operators' reaction time and prevent overload in a high target and threat density environment.

The fruitful interaction with the audience confirmed the unique opportunity offered by this classified symposium to bring together experts working in the relevant sciences as well as the user community, and affiliated either with academia, industry, government organisations, or military services.

Technologies des systèmes de mission

(AGARD CP-600 Vol. 2)

Synthèse

Les progrès des technologies d'acquisition, de traitement et de distribution de l'information permettront à des concepts de systèmes innovants d'améliorer significativement les performances des missions militaires.

Pour faire le point sur ces principales avancées technologiques, le symposium qui regroupait 24 présentations était organisé en cinq sessions portant respectivement sur:

-1- **Les concepts de conduite de mission**, qui introduit le sujet, présente les besoins en technologie et traite l'exemple des avions tactiques sans pilotes;

-2- **Les capteurs et la guerre électronique**, qui montre comment les technologies émergentes en électro-optique et radiofréquences peuvent améliorer la connaissance de la situation tactique, mais peuvent également mettre en échec des armements fiables auparavant;

-3- **Les systèmes d'information et de communication**, qui met en évidence l'intérêt de combiner des développements militaires spécifiques aux produits qui résultent des besoins du marché, ainsi que l'importance de prendre en considération l'environnement du champ de bataille;

-4- **La fusion d'information et l'intégration des systèmes de mission**, qui montrent notamment comment la fusion de données, nécessaire pour adapter le flux d'information à l'opérateur humain, peut améliorer substantiellement la précision et la fiabilité des données;

-5- **La simulation des systèmes**, qui met en évidence le rôle éminent des technologies de simulation pour la conception optimale de nouveaux systèmes militaires, l'évaluation des systèmes existants, l'entraînement des opérateurs, et conduit au concept d'environnement synthétique.

Sur la base de ces technologies émergentes en évolution rapide, les présentateurs ont construit une vision de systèmes d'armes futurs capables de fonctionner dans des environnements hostiles, par tout temps, de jour comme de nuit. Ils ont également montré comment la combinaison de capacités d'évaluation autonome de la situation, de canaux de communication fiables et d'aides à la décision en temps réel pourra réduire le temps de réaction des opérateurs et éviter la saturation dans une ambiance à haute densité de cibles et de menaces.

Les fructueux échanges avec la salle ont confirmé le succès de cette manifestation, qui a permis de réunir des experts scientifiques et la communauté des utilisateurs potentiels, en provenance des milieux académiques, industriels, et des agences gouvernementales et militaires.

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Preface

In the Spring of 1997, AGARD (NATO's Advisory Group for Aerospace Research and Development), which was celebrating its 45 years of dedication to the improvement of military and civilian aerospace research and development in the NATO nations, held a major conference on "Future Aerospace Technology in the Service of the Alliance" at the Ecole Polytechnique at Palaiseau near Paris, France. The conference comprised three main parallel symposia, three forward-looking plenary sessions, and a presentation of the results of a two-year visionary study entitled "Aerospace 2020"*. Each symposium was organised by two AGARD Panels, with contributions from the Aerospace Medical Panel.

The papers presented at the conference are contained in this and three other volumes, one of them classified.

This volume contains the papers from the symposium on "**Mission Systems Technologies**", which was organised by the 'Mission Systems' and 'Sensor and Propagation' Panels (MSP and SPP). It had sessions on:

- Mission Management Concepts
- Sensors and Electronic Warfare
- Information and Communication Systems
- Information Fusion and Mission Systems Integration
- System Simulation

Volume 1 contains the papers from the three plenary sessions:

"Future Directions in Aerospace Systems"

"Future NATO Trends and Mission Scenarios"

"Human Machine Interaction in the Future";

and the papers on "Affordable Combat Aircraft"

Volume 3 contains the papers on "Sustained Hypersonic Flight".

*The results of Aerospace 2020 are contained in an Advisory Report, AR-360, "Aerospace 2020". Vol. I is the Summary, Vol. II contains the full text of the report, and Vol. III contains supporting papers. It is planned to issue translations into French of volumes I and II later.

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INTELLIGENT DECISION AIDS FOR HUMAN OPERATORS

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1 OVERVIEW

The paper describes the concepts and architectures of intelligent decision aids, which are designed to support human operators in complex mission systems. It starts with a discussion of models for human decision making. These models are used to develop the concepts for intelligent technical devices - like monitoring or diagnosis systems for situation assessment, planning or decision aiding systems for the preparation of actions - which are built to support certain subfunctions in the human decision making process. Several examples of decision aids are presented, which have been developed in the USA, France and Germany. The goal is that the detailed presentation of these projects, together with the discussion of experiences and lessons learned from the implementations shall help potential builders of intelligent decision aids to design similar systems. The areas of application of these decision aids range from air vehicle management and aircraft mission management to air traffic management and command and control systems. The principle of coupling work systems for the modelling of complex and distributed decision making processes is discussed and applied to air traffic management and command and control.

2 FUNCTIONAL ANALYSIS OF DECISION MAKING IN MANAGEMENT TASKS

Classical control theory has enabled the engineers to transfer such human operator functions to machines (control systems), which require no explicit handling of knowledge. The advent of symbolic data processing, neural network and artificial intelligence techniques makes it now possible to design automatic systems also for functions which make explicit use of *knowledge* stored in computers. Such functions are performed, for example, in the cockpit of a military or civilian airplane, at an air traffic controller's work position, at a mission planning work station or in a command and control center.

2.1 Basic Functions in Problem Solving

Problem solving can be analysed by considering the general structure of human behavior. The goal-directed interactions of man with the surrounding world can be decomposed into the functional elements of the so-called *recognize-act-cycle* [1,2] (or stimulus-response-cycle):

a) MONITORING: Recognize the actual state of the world and compare it with the desired state (which corresponds to the goal of the interaction).
b) DIAGNOSIS: Analyse the deviations of actual and desired state.
c) PLAN GENERATION: Think about actions to modify the state of the world.
d) PLAN SELECTION: Decide about the necessary actions to reach the desired state.
e) PLAN EXECUTION: Take the necessary actions to change the state of the world.

For many simple tasks a person's physical sensors (eyes, ears, etc.), his brain and his physical effectors (arms, legs, etc.) are sufficient to carry out these functions. This is called "manual interaction". More demanding tasks (e.g. flying a military airplane) go beyond the capabilities of his physical sensor/effector equipment. Therefore, man has invented a great variety of *tools* to support his interactions with the world. The tools may support ("semi-automatic interaction") or even replace the human functions ("fully automatic").

Generally, knowledge-based human functions are required to solve a problem in the surrounding world. In these cases, the information processing carried out by the human brain in order to find a solution of the problem can be described in a similar way by the following chain of functions:

- Recognition of a problem in connection with the actual state of the world and its representation in a "mental model". Definition of the desired goal state.
- Construction of potential actions (control strategies) to bring the surrounding world from the recognized problem state to desired goal states.
- Selection of criteria to evaluate the different control strategies.
- "Mental simulation" of the effect of the control strategies on the world to assess their efficiency.
- Evaluation of the possible control strategies.
- Selection of the appropriate control strategy to "best" drive the surrounding world to the desired goal state.

2.2 Man-Machine Interaction in Work Systems

In the industrial society many of the human interactions with the world happen in so-called *work systems* [3,4,5,6]. The *goal* of a work system is to fulfill a certain task, for which it has been built. It normally consists of the elements (see **Figure 2.2-1**): *Operator*, *Work Object* and the *Tool(s)*. The tools are devices or machines which help the operator to fulfill the task. The system elements interact with each other through the operator- and the work-object-interfaces, with the goal to produce a certain output, the *product*.

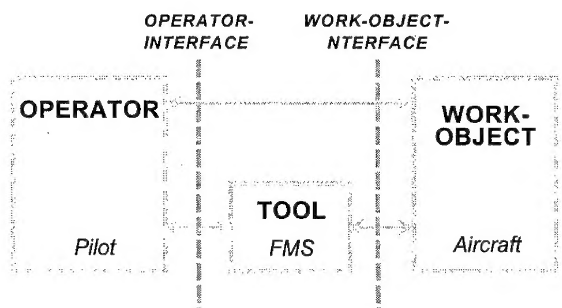


Figure 2.2-1 Declarative Representation of a Work System

The operator can interact with the work-object directly (*manual operation*) or with the help of a tool (*semi-automatic or automatic operation*). The declarative representation which describes the elements making up the work-system in Figure 2.2-1 is instantiated in that Figure with the situation of a pilot in the cockpit of an airplane. Here the operator is the pilot, the work-object is the airplane and the tool is the Flight Management System (FMS) of the aircraft. The goal is to fly the airplane in accordance with the flight plan (or the mission plan in the military case) subject to the ground rules of safe flight and possible directives of Air Traffic Control (Flight Management).

The combination of operator and tool will be called *Man-Machine System* in the following text.

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 2.

Another (complementary) way of regarding the work-system in Figure 2.2-1 is the procedural (or function-oriented) representation in **Figure 2.2-2**, which describes those functions performed by the man-machine system which are required in order to reach the goal - a safe flight according to the mission of the aircraft.

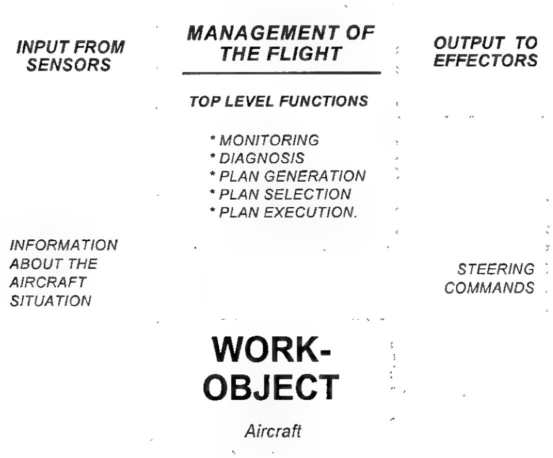


Figure 2.2-2 Procedural Representation of a Work System

One can describe the top level functions also in this case as

- Monitoring
- Diagnosis
- Plan generation
- Plan selection
- Plan execution.

In manual flight, the pilot transforms the aircraft state into its desired value, feeding the output of the work-process (the control commands) to the effectors (the actuators of the airplane). In the case of a semi-automatic or automatic flight, tools (like the Flight Management System) contribute to performing (partially or totally) the top level functions.
It will be shown in chapter 4 that complex aerospace systems (e.g. air traffic management systems or command and control centers) can be represented as networks of coupled work systems.

2.3 Functional Architecture of Management Functions

The examples discussed in this paper are related to the *management* of aerospace systems. Based on the results of a former AGARD Working Group [7], the general structure of such management functions can be described as shown in the **Figure 2.3-1**.
The functional elements of the management function are arranged in a certain *functional architecture*, and they have been grouped together in the more general functions

- situation assessment
- plan generation
- plan implementation, and
- coordination.

The *coordination function* in this architecture controls the execution of the other individual functional elements, and coordinates the total management function with other work systems.

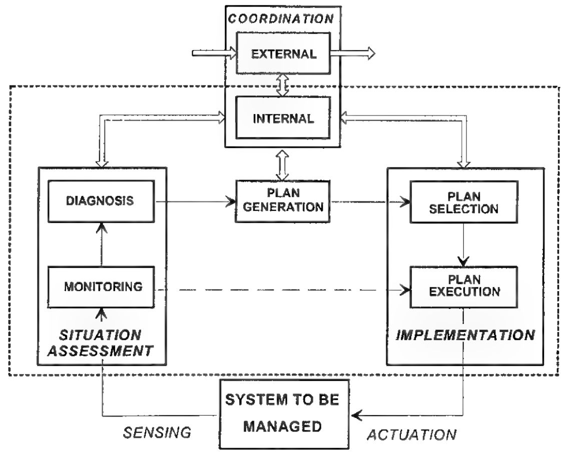


Figure 2.3-1 Structure of Management Functions

3 EXAMPLES OF DECISION AIDS FOR AIRCRAFT PILOTS AND AIR TRAFFIC CONTROLLERS

3.1 Approach Procedures Expert System (APES)

3.1.1 Introduction

The approach and landing phase of flight is considered to be one of the most workload intensive of all the phases of flight. In fact, recent studies have shown that 25-50% of civilian aircraft accidents occur during this phase [8]. A major factor contributing to these incidents is the extensive cognitive demand placed upon the pilot [9]. The pilot must recall and apply specific instrument flight rules, remember correct task sequences, and calculate timings, while simultaneously controlling the aircraft and monitoring its performance. In addition, the pilot must integrate information from multiple sources and replan according to air traffic control's (ATC's) redirection. Because of the extensive cognitive load, number of procedures, and „rules of thumb" associated with the instrument approach, the instrument approach domain is well-suited for a decision aid application.

3.1.2 Objectives

The goal of this study was to assess the usefulness and performance of a prototype decision aid, Approach Procedures Expert System (APES), for flying instrument approaches by evaluating it in a pilot-in-the-loop simulation. Because the decision aid is inseparable from its interface, both the decision aid and the pilot-vehicle interface (PVI) were evaluated; however, the emphasis of the study was placed on the value of the decision aid advice. The objectives of the study were to:

(1) Assess the *effectiveness of APES* for supporting approach tasks and its potential for reducing pilot workload, increasing situational awareness, and improving performance.
(2) Assess the *performance of the decision aid* to determine if APES advice was accurate and timely enough to assist the pilot in flying instrument approaches.
(3) Assess the *understandability and usability of the pilot-vehicle interface* to determine if the interface allowed the pilot to easily interpret and use APES advice.

3.1.3 Approach Procedures Expert System (APES)

The intent of the APES prototype is to reduce pilot workload, increase situational awareness, and improve performance and

safety. The APES simultaneously monitors aircraft performance, informs the pilot of appropriate corrective actions when deviations occur, and provides procedural advice according the phase of the approach (i.e., holding, initial approach, final approach, missed approach). To accomplish this, the APES functions in two assistant roles: as an „advisory copilot" and as an „advisory pilot." As an „advisory copilot" the decision aid advises and prompts the pilot as a copilot would in a crew environment, such as advising when the aircraft deviated from assigned parameters (e.g., altitude, airspeed, etc.). As an „advisory pilot" the decision aid provides guidance relevant to the instrument flight rules (IFRs) needed for the specific phases of the approach.

Audio, a natural form of communication that would exist between the pilot and copilot, is the primary pilot-vehicle interface for the APES. Visual messages are employed for redundancy and when it would be impractical to use audio. The following sections describe the developmental process, the APES system architecture, and the Pilot-Vehicle Interface (PVI).

3.1.3.1 Overview of the APES Developmental Process

The first step in the development of the APES was capturing the expertise of experienced pilots through a knowledge acquisition process. A knowledge engineer conducted an iterative interview process with several subject matter experts (experienced in-house pilots). This process identified the precise steps that were necessary for flying the various phases of an approach. The knowledge engineer then modeled the actions recommended by the expert pilots and created process flow diagrams. The process flow diagrams served as a basis for the APES algorithm.

The APES prototype was then integrated into a simulator and tested in an iterative check-out process. Test approaches were flown with various flying patterns to exercise all of APES decision points and to determine if APES was functioning as intended. Design flaws were identified and corrected. Upon completion of the check-out process, a verification test was conducted. An in-house pilot, unfamiliar with the APES, flew all of the approaches that were used in the study. Design deficiencies, that went undetected during the iterative design process, were identified and corrected. APES was then formally evaluated in the current study.

3.1.3.2 APES Architecture

The APES prototype system consists of the following basic components. (The interaction of these components is depicted in **Figure 3.1-1**.)

(1) a dynamic aircraft status file
(2) a set of facts representing aircraft-specific and approach-specific databases
(3) a set of rules where the expert knowledge resides
(4) a forward-chaining inference engine which takes advantage of the speed of the „Rete" algorithm to provide faster performance

APES Inputs

As depicted in Figure 3.1-1, input to the APES comes from three sources: current aircraft flight parameters, a database of aircraft specific facts, and a database of approach specific facts. Examples of the types of input that are used by APES include the following:

- Aircraft Status Data
  - Current Altitude / Heading / Airspeed
  - Current Navigation Aid Radial
  - Current Navigational Radio Channel
- Aircraft Specific Facts
  - Holding Airspeed
  - Fuel Weight
  - Approach Airspeed
- Approach Specific Facts
  - Holding Altitude
  - Final Approach Course.

An aircraft specific input file was created for each aircraft type in order to allow a generic APES to be embedded in aircraft (or aircraft simulators) of different types. Data for the aircraft are loaded from the corresponding aircraft specific data file during program initialization. For purposes of this study, the aircraft specific facts were limited to an F-16 aircraft. Also the approach specific facts were limited to eight approach plates; however, the APES can accommodate an unlimited number of approach plates.

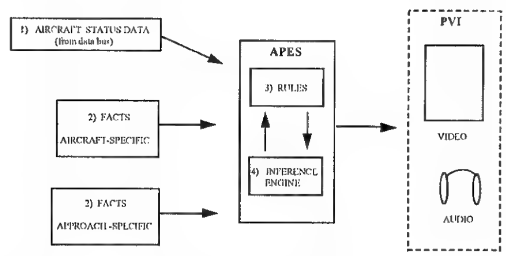


Figure 3.1-1 APES System Architecture

APES Implementation

The expert systems development tool used for this study was the C Language Integrated Production System (CLIPS) developed at the NASA Johnson Space Center [10,11]. CLIPS is a distinguished member of the OPS-5 family of expert systems shells, and has been extensively used in many applications, including a variety of NASA missions. The CLIPS inference engine uses the highly efficient Rete algorithm, which contributes to CLIPS' excellent run-time characteristics. CLIPS avoids the timing problems associated with slower running expert systems because the Rete algorithm does not reconsider a rule (that has already been executed) for activation until a subsequent change in the value of one or more of its antecedents has occurred.

3.1.3.3 APES Pilot-Vehicle Interface

The primary pilot interface for the APES is voice message presentation. For example, if the pilot deviates more than +/- 2 degrees from course, the APES „advisory copilot" component would compute a heading to re-intercept the course and announce „Turn/Come Right/Left Heading XXX." Once reestablished on the course, APES would then announce „Maintain (course) XXX." To output a voice message, the APES passes a text string to the voice module of the Silicon Graphics host system. The Silicon Graphics system then generates the voice message by combining words that are listed in a vocabulary database of approximately 50 words.

APES voice messages are reinforced with the visual presentation of text information. The APES continually displays updated target values for radio channel/frequency, altitude, airspeed, heading, and course in a scratchpad area to allow the pilot to manipulate appropriate command marker and course indicator settings. APES also displays current (target) values for radio, altitude, airspeed, heading and course on a dedicated Cathode Ray Tube (CRT). This CRT is also used to display more complex textual information, such as pre-approach and final approach checklists. The cockpit displays are depicted in **Figure 3.1-2**.

3.1.4 Methodology

To accomplish the test objectives, 16 pilots flew a series of instrument approaches in the cockpit simulator. The presence of the decision aid, the orientation of the electronic approach plate

(EAP) and task difficulty were varied across approaches. Task difficulty was implemented at two levels, high task loading and low tasking loading, to determine the benefits of the APES in both task environments. Two EAP orientations were also investigated, North-Up and Track-Up, to determine if the utility of the APES would vary with EAP orientation.

3.1.4.1 The Simulator

The APES study was conducted in a single-seat fighter cockpit simulator containing five color CRT displays (only four of which were used), three banks of programmable switches, an A-7 throttle, and a force-control stick. Two speakers were located behind the cockpit seat for announcing the APES audio advice. Figure 2 shows a layout of the cockpit. An F-16 aeromodel was used to drive the simulator.

3.1.4.2 Electronic Approach Plate Formats

The Electronic Approach Plates (EAPs) were electronic depictions of the paper approach plates that pilots would use for flying instrument approaches. The EAPs were developed using a vector product format.

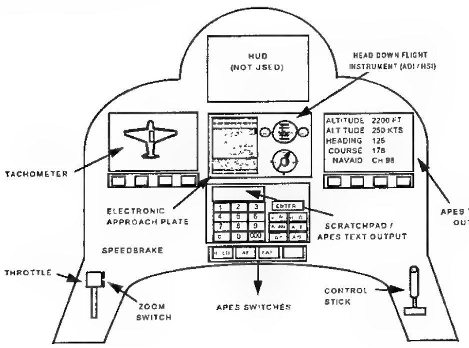


Figure 3.1-2 Cockpit Layout

Unlike the paper approach plates, the EAPs display current aircraft position. For this study, aircraft position was displayed in two map orientations: North-Up and Track-Up. In both orientations, the aircraft symbol was fixed in the center of the display and the EAP moved underneath it to reflect the aircraft's current position. In the North-Up orientation, the *aircraft symbol rotated to reflect the aircraft's current heading*. In the Track-Up orientation, the *EAP rotated to reflect the aircraft's current heading*. **Figure 3.1-3** illustrates an example EAP used in the study.

3.1.5 Results and Discussion

The results showed that the APES enhanced the pilot's ability to perform instrument approach tasks (**Objective 1**) compared to flying the approaches without APES assistance. With APES assistance, pilots deviated less from assigned altitudes, especially during high task loading. They also deviated less from assigned airspeed during the initial and final approach phases. Pilots rated their workload lower with APES, particularly during high task loading, and their situational awareness higher. Study findings also indicate that APES effectiveness was not influenced by the electronic approach plate orientation (i.e., north-up or track-up).

Regarding the performance of the decision aid (**Objective 2**), pilots rated APES' logic, consistency and timeliness as above „moderately acceptable"; however, some refinements were indicated. Pilot comments indicated that the deviation tolerance windows for APES voice activation were too stringent, especially the airspeed and altitude voice prompts. Also the timeliness of the procedural prompts, given at the approach fixes, were reported as being „hurried." In general, pilots thought that APES would improve flight safety, but some expressed concern with the consequences of being over-reliant on the system.

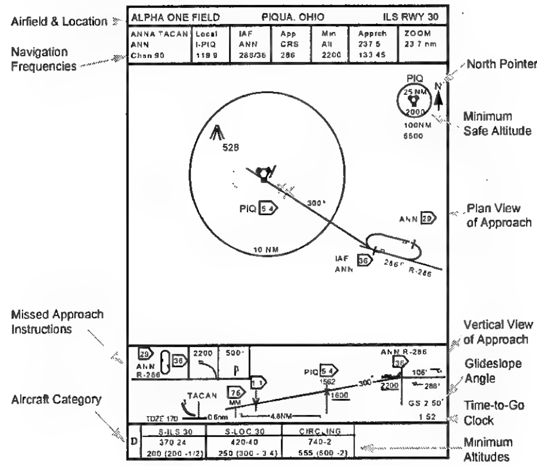


Figure 3.1-3 Electronic Approach Plate (North Up)

Pilots rated the APES PVI as „acceptable" (**Objective 3**); however, refinements were indicated. Pilots commented that the phraseology of APES voice prompts should be more specific, particularly during the final phase of the approach. Pilots also commented that the PVI should allow for pilot settings and/or adjustments to tolerance values for decision aid activation.

In summary, pilots reported that APES was beneficial in assisting them perform instrument approaches; however refinements to both the decision aid algorithm and the pilot-vehicle interface were indicated.

3.1.6 Lessons Learned

As with any decision aid, careful consideration needs to be given to the known disadvantages associated with semi-automated systems. Because low-level decision making processes are automated, the pilot may view the system as a black box that generates outputs from inputs through some unknown mechanism, such as the algorithm. This may impair pilot confidence in the system and result in the pilot completely ignoring the advice of the decision aid. Conversely, too much trust and over-reliance on the decision aid may lead to reduced pilot situational awareness, which in turn, could adversely affect flight performance if the decision aiding system fails or an emergency occurs.

One way to mitigate the possible effects of reduced situational awareness and system confidence is through proper training of the decision aid logic. This training would enable the pilot to develop an accurate mental model of the reasoning behind the advice [12]. Equally important is proper design of the pilot-vehicle interface to facilitate the human-computer interaction and allow the pilot to easily interpret the decision aid advice.

An effective decision aid may also need to include user-selectable options as part of its design, giving the pilot flexibility in configuring the PVI. For example, the pilot may find it useful to configure display modes (audio or visual) for certain types of advice (e.g., altitude, airspeed, course). The pilot may also find it beneficial to set the priority levels (e.g., primary and secondary) of the various advice types, as well as, adjust their tolerance windows (e.g., +/- 100 feet for altitude deviation).

3.2 Copilote Electronique

3.2.1 Introduction

Since 1994, the Technical Service for Aeronautical Telecommunication and Equipment of French DGA (STTE) launched an exploratory development program concerning a high level decision aid, using Knowledge-Based System (KBS) technology for an advanced combat Aircraft. This french project for an in flight mission planning Decision Aid is called "Copilote Electronique" [13]. The exploratory development program is lead by Dassault Aviation with the support of many industrial and scientific partners (SAGEM, Dassault Electronique, Matra Défense, Sextant Avionique, IMASSA, ONERA...). It aims at introducing, this kind of decision aid within a 2010 horizon for a future Rafale standard (The Rafale aircraft will enter the French Air Forces at the start of the next century).

3.2.2 Operational Objectives

- *The operational objectives of the Copilote Electronique are surveyed in order to precise the domains of assistance that are relevant for such a system.*

Before the launch of the Exploratory Development an action was initiated by DRET the french military research agency to survey the need for pilot assistance in french airforce programs and the feasibility of KBS as a potential technical answer. The need was expressed by senior pilots of the french airforce and navy, with experience of Mirage F1, Mirage 2000 and Super Etendard. The cognitive analysis of pilots activities was conducted by CERMA (Centre for Medical studies and research in Aerospace).

Within the context of the Copilote Electronique program this initial survey was completed and reviewed in front of the forecasted definition of the Rafale missions and system standards. This involved a specialist of the Rafale program from the CEAM (French air force test center) as well as Dassault test pilots currently involved in the definition of the new program.

This section do not address specific requirements linked with the Rafale program but the generic needs of an on-board mission planning activity in a future combat aircraft.

Conducting penetration missions in hostile territory has always raised problems of workload on single pilot. Regardless of aircraft configuration and avionics the planning activity is a very difficult task for the pilot in flight. This includes route selection, ECM employment (like activating and shutting down jammers, throwing decoys...), flight monitoring (following profile, respecting timing, handling communication with C3I...), attack planning and weapon selection... This overload problem has generally been solved by applying strict mission control rules over a very detailed ground-based mission preparation.

It is recognised for example that in a typical Penetration Mission at low altitude and high speed within enemy territory, a pilot is following a strict time schedule with little possibilities to divert from it. For instance at an altitude of 300 to 500 feet and a speed of 500 knots only a few seconds of delay over the way points can be accepted. If such timing is not followed coordination between friendly ressources is in danger, the efficiency of weapon delivery is lowered and possibly, the firing of the aircraft by friendly ground defense will happen when crossing back the Front Edge of Battle Area (FEBA). **Figure 3.2-1.**

The extreme time pressure imposed on pilots of combat aircraft makes the planning activity very complex and dynamic. With such an extreme time pressure, in-flight planning could be considered as totally unrealistic, but it must be recognized that most of the time real missions will be disturbed by unexpected events. This leaves no choice to the pilot who needs replanning.

Many of those unexpected events have been listed in the domain of aircraft ressources. One may mention engine failures, jammed positioning systems, sensor default... They are also numerous and frequent in the tactical domain. For instance one will encounter hostile Conter Air Patrol aircrafts (CAP), unknown ground missile sites (SAM), electronic counter measures... There are of course perturbations due to the natural mission conditions such as weather evolutions, unregistrered ground obstacles... Finally one have to mention coordination problems between raid and escort patrol or Command and Control aircraft (AWACS) as well as possible human errors.

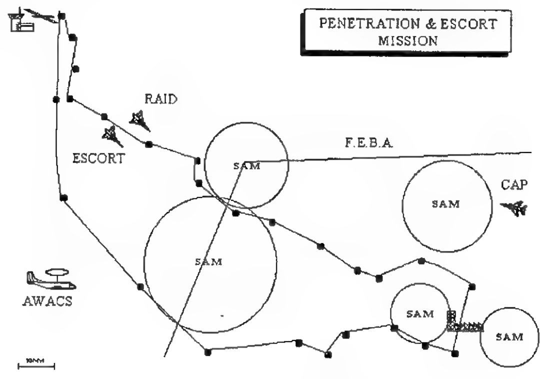


Figure 3.2-1 Penetration and Escort Mission

Therefore a strictly nominal execution of a mission plan prepared on ground is very unlikely to happen according to the experience of Mirage F1 CR or Mirage 2000 operations as well as Rafale extrapolations. Even simulation campains will show frequent perturbations with the necessity for the pilot to react by in flight mission planning. A recent Rafale simulated test of a sweep mission exemplified the interest of some pilot support in heavy workload situation.

In such cases the functional requirements of pilot planning task ranges from flying activities, navigation, ressources management, information pick up, to tactical response elaboration.

For instance an Air to Air Engagement during an escort mission was analysed in detail. In case of ennemy engagement, a pilot has to planify an adapted behavior to analyse the tactical situation including platform manoeuver and sensor control. He needs to coordinate the friendly actions through communication with the penetrating raid bomber leader and with its fighter wingman. He exchanges tactical information, selects tactics, assigns target and he instantiates a proper offensive plan including weapon preparation, launch point calculations, flight path trajectories generation, evaluation of kill and survival predictions...

In conclusion of this section it can be assessed that a requirement for in flight mission planning is perceived in future low altitude high speed penetration missions and air to air escort missions (this is not to say that in flight planning is not needed on other missions such as air to air interception at high altitude but this analysis was not carried exhaustively within the scope of the project).

The planning task not only concerns navigation strategies but also tactical offensive and defensive management as well as aircraft ressources monitoring. These many planning concerns overlaps during active mission phases such as air to air engagement. Consequences of bad planification as taking wrong decisions, acting too late, or executing improperly the plan, are generally intolerable. It may result in a crash, or an unsuccessful mission, or the loss of aircraft and pilot ...

A single pilot with current avionics is unlikely to perform such in flight planning complex task without errors. A need for assistance is perceived, leading to increased autommation as well as planning support. It was noticed during the analysis phase of the Copilote Electronic that there is a general preference for systems providing assistance in tasks such as calculating fuel, plotting routes, identifying risks... Pilots really

care for better situation assessment in the planning process. This was well expressed by Major G.W. Breeschoten in his keynote address of Guidance and Control Panel 53rd Symposium [14]:
"I do not want the system to think for me, at least in the sense that it prescribes my tactical actions. It can to some extent think with me."
Nevertheless, as critical decisions are to be taken on uncertain or tactical aspects of mission, aircraft designers often rely on pilots judgement. This tendency is even currently required by Air Forces.
As a result of this requierement analysis the Copilote Electronique project is oriented toward a multi-agent (or multi-assistance) organisation that best express the human resonning in the guidance and control domain. For the development phase of the program it was then decided to consider the expert domains that pilots distinguish in the conduct of penetration and escort mission.
These domains are:

- **Aircraft system management** (« domaine Avion »), including:
  - System evaluation
    - Monitoring discrete events and continuous signals.
    - Assessing real avionic systems states and dependability.
  - System planning
    - Planning the avionic systems reconfiguration.
    - Scheduling of action & ressources according to the plan.
- **Tactical management** (« domaine Tactique Sol » & « domaine Tactique Air »), including:
  - Tactical assessment
    - Analysis of friendly & foe forces.
    - Elaboration of forecasted evolutions.
    - Assessment of risk/efficiency according to present plan.
  - Tactical planning
    - Planning tactics according to the threats and pilot strategies.
    - Scheduling actions and ressources according to the tactics.
    - Handling conflicts among proposed tactics.
- **Mission management** (« domaine Mission »), including:
  - Mission condition assessment.
    - Mapping of pre-mission meteorological brieffing onto possible routes.
    - Mapping of pre-mission geographical data onto possible routes.
  - Route planning
    - Selecting re-routing options accoring to the updated mission context.
    - Planning new routes.
    - Monitoring possible routes with quality estimates.
- **Man-machine coordination** (« domaine Coherence des assistances »), including:
  - Pilot behavior assessment.
    - Mapping pre-mission strategic option to in-flight planning.
    - Inferring pilot intent from observed actions.
  - Planning management
    - Driving experts planning efforts toward a common goal.in accordance with pilot strategy
    - Insuring proposed plan quality
  - Dialogue management.
    - Presenting relevent informations to the pilot
    - Handling pilot querries.

3.2.3 Ergonomical Design

- *The advantages of a cognitive assistant approach over an automatic planing approach and the ergonomical rules settled by the project to facilitate in flight Pilot<->System relationship are presented showing the "Copilote Electronique" orientations in that respect.*

To design the proper decision aid it is necessary to analyse the level of autonomy best adapted to the in flight planning process.
In front of the increasing complexity of avionic systems and weapon systems it is certainly desirable to design systems capable of taking responsibilty of lots of pilot decision activities. The present technological push, best exemplified by the well known knowledge-based systems, expert systems, constraint programming tools, neural nets... leaves an open field to the dream of full automation. Of course some caution should be taken in terms of feasibility for these techniques in real time avionics. As Wiener and Curry showed [15], full automation can have serious drawbacks with a risk in the long term of having operators unable to conduct the missions.
Various embedded functions, such as navigation, piloting, aircraft status management, weapons system management, and in some extension sensors management have been successfully automated by classical software engineering methods, but the addition of such separate and independent automated functions is more and more difficult to control in real time situations by human pilots.
Automated functions are intended to increase in number and complexity, in the foreseen tactical context of year 2010. Such context is characterised by a great number of various possible threats, with electronic war systems and new sophisticated weapons. Operational experts think that future pilots will have some difficulties with this combinatory explosion of information sources unless being assisted in their reasoning tasks.
Within the "Copilote Electronique" project the tasks were cautiously analysed in terms of potential for automation and/or assistance. The first work was based on the guidelines of the AGARD advisory report on improved guidance and Control for the automation at the Man-Machine Interface [16].
These guidelines expressed that tasks requiring highly accurate responses, fastidious and repetitive actions, and exhaustive calculations are good candidate to automation. On the other hand, tasks requiring judgement, multi-sensory information gathering, hypothetical reasoning, contingency reaction... are best suited for a "Man in the loop" design.
Planning tasks are certainly of the second type. Those tasks like system reconfiguration, ressources scheduling, navigation, fuel monitoring threat analysis, threat avoidance, threat engagement, command control and communication, sensor control and weapon management were structured according to the expert domains:

- System management
- Tactics managment (air-air and air-ground)
- Mission management

In the System area, planning is more often an optimization of fine grain plan in front of the flight parameters evolution and generalised state of the navigation and weapon systems (including faulty states).
In the Tactics area, planning is reactive. Threats are poping up as unexpected event and disrupt from the planified behavior established on ground during the preparation phase.
In the Mission area, the result of the mission preparation remains the guide for all in flight planning. The task here consists of adaptations of the nominal plan, plan refinement in a precise context, choice of alternative plans...
At this stage of the design the approach was oriented toward a human centered design. This was based on human factors evidences from the aviation history, which are addressed in the "Copilote Electronique" team by IMASSA/CERMA [17].
This study resulted in "user oriented rules" that has to be used in the design of the Copilote Electronique

Those rules can be summarised as follows:

(1) pilot anticipates and needs anticipation assistance on contrary of "classical engineer designed" assistance which are often too reactive,
(2) pilot's decisions reflect often compromises between mental load and ideal response to the situation, so pure optimality is not to be researched if pilot has no sufficient time to understand,
(3) following their own personal skills, different pilots may organise work differently, assistance must be adapted to these skills,
(4) assistance must be homogeneous, and it will be preferable to rely on specialised expert for each operational domain (e.g. Strike or Air Defense expertise) so resulting assistance will produce constant understanding interpretation model that will avoid surprises for pilot,
(5) assistance must know and respect its own limits,
(6) system design may use "what if" approach to be less reactive,
(7) dialogue must be adapted to context, pilot intents and pilot load,
(8) dialogue must be space oriented and interactive, better use vocal media than written, but avoid saturation,
(9) respect logic of pilot understanding, that means rely on the understanding model designed with expert pilots.

The french Copilote Electronique project is oriented toward a cogitive assistance as a consequence of this ergonomical analysis.

3.2.4 Functional Architecture

- *The organic architecture established for the "Copilote Electronique and the proper mechanisms supporting the cognitive assistant approach of mission planning are described.*

In order to achieve the main objective of demonstrating the concept of a cognitive assistance for future combat aircraft it is necessary to organise the selected expert domains that will perform the required functionalities of in flight decision aid.

The Copilote Electronique project finalized such an architecture by the end of 1994. **Figure 3.2-2.**

The top level organization of the expert domains in the Copilote Electronique is in accordance with the Functional Decomposition of Generic decision system in Guidance and Control as proposed by AGARD Working Group 11 [18].

The two main activities of situation assessment and planning are represented in each of the expert domains. All the expert domains are communicating with others to enrich their vision of the situation and to elaborate plans. The coordination activity is taken in charge by a specific expert supervising the others.

An expert domain, absorbs high rates of raw information, select and highlight the more crucial ones, before initiating dialogue with the other experts. Raw data is provided by the existing technical functions of the Navigation and weapon system assuming that a data sharing mecanism is avalable (it is the case with Rafale and M2000 type of system).

The planning reasonning layer of each domain take entries from the assessment level. Expert description of the situation are not propagated to each domain but relevant informations can be accessed on request. Planning directives are passed by the supervising expert to the concerned specialists according to the problems encontered. Such directives includes, problem scope, constraints, and pilot strategies. The experts reason in a manner adapted to current situation and mental load of the pilot. They consider a restricted set of actions choice for the pilot and examine all consequences before proposing them.

Dialog with the Pilot is handled at the supervision expert level. It insures that a single coherent proposal will be presented by the group of expert domains. It also minimize the informational woarkload of the pilot and handles the pilot queries through the use of « regular » man-machine interface of the Rafale aircraft.

The external world perception, the communication with other agents and the plan execution are not part of the Copilote Electronique responsibility but it can be assumed that these activities are present in the current Navigation and Weapon system (SNA) in which the Copilote Electronique is integrated.

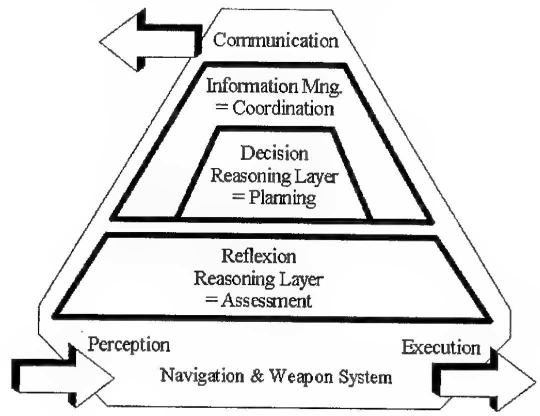


Figure 3.2-2 Functional Architecture of the Copilote Electronique

The dynamic behavior of the Copilote Electronique is driven by a cyclic assessment of the situation by the expert domains (the period of the cycle differing from one expert to another) and an event driven planning activity based on the warnings issued by the assessment layer. The planning activity includes several steps of generation driven by the experts best suited to the revealed problem and the pilot strategy. Those steps are followed by qualification treatment. Qualification is performed by all the expert domains so that the quality of the proposed solution is seen globally and not only by a single domain with possible conflicts with other fields. In case of insufficient quality constraints are posted by the expert domain to help the other in refining their proposal. Once finished the planning activity gives results to the dialog manager. Plans are joined to situational information to be presented to the pilot. Two levels of dialog are handled (rich or succint) in order to adapt the information flow to the pilot workload.

The **Figure 3.2-3** present this process.

3.2.5 Development Status

- *A short overview of the knowledge-based development process engaged is given*

The goal of the functional development, launched in 1994 for a three years duration, is a ground simulation, without real time constraints, to illustrate the potential of the "Copilote Electronique" in situation of strike and escort missions, with low altitude penetration constraints. The software architecture at this stage is resolutely a cooperative set of expert modules mapping the expert domains [19]. To conduct this development Dassault Aviation set up a consortium based on the french industrial competences.

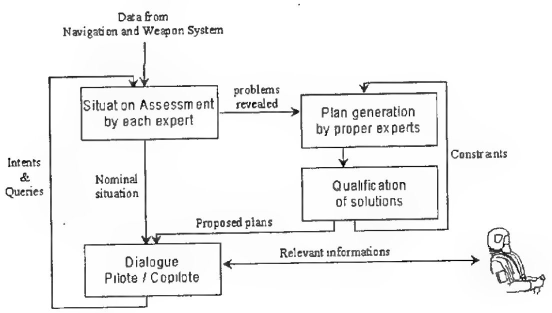


Figure 3.2-3 Block Diagram of the Copilote Electronique Functions

Responsibilities within the consortium are:

- Ergonomics rules and knowledge acquisition methods and verification tasks
  -> IMASSA/CERMA

  System Status Assessment and Management
  -> SAGEM
- Tactical Situation Assessment and Management (Ground threat and defensive Counter Measures)
  -> DASSAULT ELECTRONIQUE
- Tactical Situation Assessment and Management (Air threat and offensive Weapons)
  -> MATRA DEFENSE
- Mission Conditions Assessment and Mission Management
  -> SEXTANT AVIONIQUE
- Pilot Assessment, action plans assessment, relevant information management and man-machine interface
  -> DASSAULT AVIATION

Knowledge engineering techniques are for expertise initial design. With IMASSA, a specific method for eliciting and formalising pilot's expert knowledge was studied and is used. It is supported by a formalisation tool called X-PERT. It is confirmed by present campains that pilot expertise can be collected coherently in all the expert domains and that generic behaviors (not linked with a specific Navigation and weapon system) can be used in the expert modules. Generic expertise has to be supplemented by extensive knowledge evaluation and correction in simulator. in order to represent specific behaviors linked with the new system like Rafale. The main issue for the future design is to accept expertise from pilot during operational life of the system.

The technical specification is driven toward a flexible heterogenous implementation paradigm. The Copilote Electronique expert modules are organised in a multi-agent system using Distributed Artificial Intelligence techniques [20]. Another very important technical issue is the definition of a common **"plans and goals" exchange language** between all specific assistance modules, and great efforts are made to maintain this common message glossary. Within the functional development Dassault Aviation proposed an exchange language called LDI which provides a CORBA like facility for object communication.

A unifying technical principle is adopted to facilitate the architecture design via the **intent planning paradigm**. This principle is essential to fulfil general ergonomics constraints: assistance must not participate to the signalled existing overloading factors. Intent recognition is a challenging but promising direction and can be made easier by extended preparation mission plans and procedures (for each pilot activity) that will be perhaps the new "automated and personalised" check lists version of the future [21].

At present, a mock-up is implemented. It uses a set of unix workstations (one for each expert domain) linked to a Rafale simulator with « engineer » type of interface. The mock-up shows non real time behavior of the expert modules integrated in a complete Copilote Electronic system. A synthesis of the presented functionalities will be realised in spring 1997.

3.2.6 Conclusions

This example opens to the possible future developments of intelligent decision aids for in flight mission planning within future combat aircraft.

The technology is available today to provide viable knowledge system solutions to well-chosen and well-defined problems. It can be expected to see more and more successful projects on such on-board applications, as both the research, the technology and engineering skills of application developers improve.

But this process may be slower than was though. Main reason is that knowledge acquisition tasks and user oriented ergonomics rules compliance must be integrated in the overall engineering cycle.

The french Copilote Electronique project has been carefully planified considering those methodological difficulties.

After a long design phase the Copilote Electronique is now in a software development phase. The planning domains are the main drivers of this development. They are developped by french industrial partners in a federative approach. Each partner brings to the project a specific background, with a high value knowledge of his planning field and mastering of appropriate planning mecanisms. This results in a very rich but heterogeneous multi-expert, multi-industrial planning system.

The Copilote Electronique, not only reach a successful behavior in each planning field, but also achieves a coherent assistance for in flight decision aid. Special care is taken to analyse interdependancies between the various plans and to respect the rules of a good man-machine relationship. Expert pilots give feedback on the quality and acceptability of the resulting planning assistant. According to their remarks the architecture, mecanisms and knowledge of the Copilote Electronique planners can be tuned. Present scenarios give confidence on the resulting operational benefits of the assistance system.

Planning proposals will be demonstrated on a realistic full mission simulator after optimisation of the present mock-up. Real time performances of the resulting planning system will be optimised with the help of current technological progress (specially modular avionics and new software environment). It is beliefed that the key of a successful in flight planning is more in the pilots cognitive abilities than in hardware/software evolution.

The first steps of the Exploratory Development phase confirms that the distributed architecture and the Human driven design approach are good drivers for success..

3.3 Cockpit Assistant System (CASSY) and Crew Assistant Military Aircraft (CAMA)

3.3.1 Introduction

The central idea for the development of *CASSY* and *CAMA* is, to ensure that the crew will have all necessary and useful information without overloading, according to human-centered automation [22]. Design criteria were established, which aim at a cooperative function distribution between man and machine like that of two partners [23].

Both man and machine are active in parallel by assessing the situation and looking for conflict solutions at the same time. In contrast with current man-machine interaction, both assist each other while heading for the same goals. Consequently [22, Page 84] demands: „Each element of the system must have knowledge of the others' intent. Cross monitoring (of machine by human, of human by machine and ultimately of human by human) can only be effective if the agent monitoring

understands what the monitored agent is trying to accomplish, and in some cases, why." Hence, the level of understanding what each element of the system is doing should be as high as possible.

Derived from the demands on automation a knowledge-based aiding system should comply with two basic requirements [24,25]:

- Requirement (1): As part of the presentation of entire flight situation the system must ensure to guide the attention of the cockpit crew towards the objective most urgent task or sub-task.
- Requirement (2): If requirement (1) is met, and if there (still) occurs a situation of over-demanding cockpit crew resources, the situation has to be transformed - by use of technical means - into a situation which can be handled normally by the cockpit crew.

Basic requirement (1) is to ensure situation awareness of the crew. In part, it can be transferred into the functional requirement for the assistant system of being capable to assess the situation on its own.

Pilot's workload has become a critical issue as the mission complexity has grown. It is particularly desirable to reduce the need to compose the relevant information from numerous separately displayed data. The ability of the assistant system to detect conflicts, to initiate and to carry out its own conflict-solving process and to recommend and explain this solution to the pilot, gives the pilot sufficient time to cope with unanticipated events and to act reasonably (requirement 2.). This appears to be a flexible situation-dependent, and cooperative share in situation assessment and conflict resolution between the electronic and the human crew member. Automation, like recommended in the past, seemed to be very attractive. However, it has to be handled with care not to find the pilot out of the loop of conducting the mission and flying the airplane (check „automate" and come back in „manual" if necessary).

Ignoring the basic requirements, automation changes the pilot's task into automation management, merely monitoring automatic systems. Increasing workload of the crew should lead to machine initiatives for anticipating of future mission and conflict solving recommendations [25].

3.3.2 *Functional Layout of Knowledge-Based Assistant Systems*

If the above mentioned design-criteria and requirements are perfectly fulfilled, this will result in an electronic crew member which is capable:

- to understand the abstract goals of a mission,
- to assess mission, environment and system information the crew needs,
- to detect the pilot's intent and possible errors as part of situation analysis,
- to support during planning and decision making by recommendations of the conflict solver and
- to know, how to present it to the crew effectively by the dialogue manager

and the following functional layout (**Figure 3.3-1**) of an electronic crew member as a Knowledge-based Assistant Systems is to be made:

The functional module of **Situation analysis** deals with the ability to comprehensively understand a current situation. This process starts with the perception of the situational features. The machine infers from these features abstract objects of the situation. This closely resembles the human way of situation analysis. The process ends with an overall situation description, also covering weather reports, threat locations and aircraft state as well as elements like evaluated mission-goals, plans, present and future tasks, actions and deviations from estimated behavior. On the basis of the situation description the situation diagnosis process recognizes and predicts conflicts from observable indicators, caused by events in the domain of either aircraft, pilot or environment.

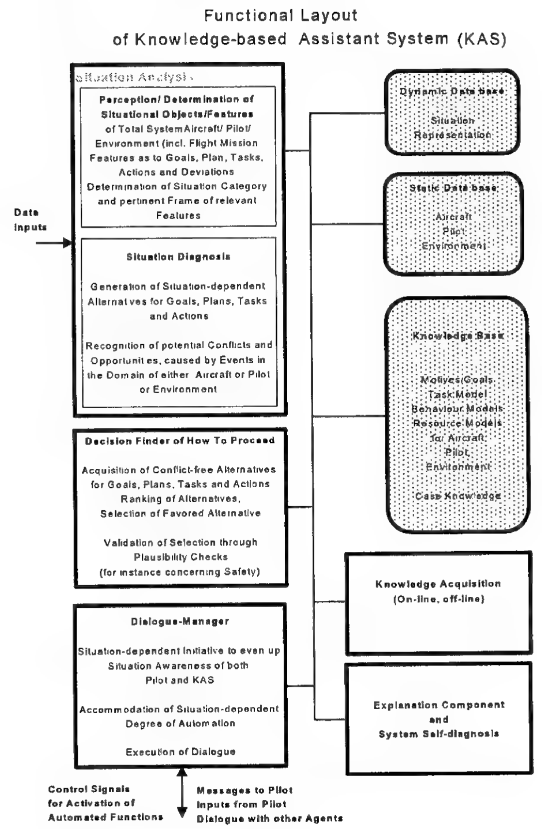


Figure 3.3-1 Generic structure a knowledge-based assistant system

Alternatives for goals, plans, tasks and actions are generated including that one, which represents the given flight plan, and all are checked with respect to potential harmful conflicts. If conflicts are detected, only the conflict-free alternatives are passed onto the conflict solver. The **conflict solving** is ranking these alternatives and selects the most favored alternative on the basis of the mission success criteria.

Dialogue management insures effective communication with the crew. This functional component as the front-end of an assistant system is to present all necessary and useful information in a way, that it is easy to comprehend. Messages to the cockpit crew should be tuned and tailored to the current situation especially with respect to the resources of the crew. Pilot-inputs to the system should allow initialization of services and decision support without tedious or distracting input actions.

Knowledge processing needs a dynamic object-orientated **representation** of the situation-describing objects. The representation covers sensor data as well as very abstract objects like the whole flight plan or, for instance, the recognized intent of the crew.

Other knowledge bases are essential to express and enable access to domain knowledge and to permit inference. Models about motives and goals, task selection, execution knowledge and demand for resources as well as behavior models are important examples of this kind of knowledge, executed by additional information about the crew member.

Static data bases for navigation purposes or threat data bases can already be considered as standard.

The expert knowledge embodied in the system has to be obtained in a systematic way. **Knowledge acquisition** appears as the bottle neck during development of the knowledge-based assistant system. Well-defined and efficient algorithms and methods have to be used to map the real world with its disguised structure and uncertainties.

In order to increase user acceptance, it is desirable that the system contains a justification or **explaining component**. First of all the user should be conscious of the rules that are applied in the algorithm to obtain a solution or system state to gain confidence to the system.

System self-diagnosis makes sure that the hints and services to the crew will be really useful. The system must be able to realize, if information concerning the actual situation might be insufficient to assist the crew, or that the system itself is not working all right and needs to be corrected.

3.3.3 Monitoring of Pilot Behaviour

As pointed out, a vital prerequisite for the machine system's capability to provide assistance in all situations is the ability of correct and comprehensive situation assessment. This means, the system must be aware not only of the aircraft and its environment but also of the crew's aims, tasks and resources. In this case the system will be able to predict information and assistance needs of the pilot crew and to organise its task support.

The machine's situation assessment process can be realized by monitoring and interpretation of the pilot actions within two loops. (**Figure 3.3-2**).

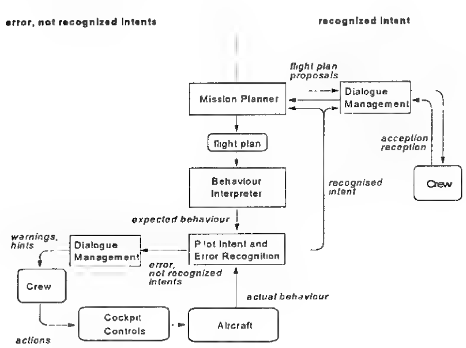


Figure 3.3-2 Monitoring and Interpretation of Pilot Behaviour

The first loop starts with the generation of expected pilot actions by use of knowledge about pilot-behaviour concerning the actual flight plan (Pilot Modelling, done by the module *Pilot Behaviour Interpreter*).

Expected crew actions are compared with the actual behaviour shown by the crew. If the actual pilot behaviour differs from the expected behaviour the module *Pilot Intent and Error Recognition* tries to figure out, if the deviation was caused erroneously. Detected errors are issued to the crew by warnings and hints which will help the pilot to correct slips. This is the normal, inner loop.

By monitoring pilot actions in the second loop as well as the mission context, the system is able to compare the pilot's actions to a set of behaviour hypotheses. In case of an intentional deviation from the flight plan, the module checks, if the behaviour fits to a given set of intent hypotheses. These hypotheses represent behaviour patterns of pilots, for example, when commencing a missed approach or avoid a thunderstorm. With the intention recognized, support like re-planning is initiated.

Humans, however, often solve complex problems using very abstract, symbolic approaches which are not well suited for implementation in conventional languages. One of the results in the area of artificial intelligence has been the development of techniques which allow the modelling of information at higher levels of abstraction.

These techniques are embodied in languages and tools which allow to develop algorithms very similar to the human logic and to maintain large knowledge bases.

The supporting technologies for the systems function of monitoring the pilot behaviour will be briefly described behind each step of monitoring the pilot's behaviour.

a) Pilot Modelling

Modelling of pilot behaviour is done in two ways. The *normative model* describes deterministic pilot behaviour as documented in pilot handbooks and air traffic regulations. Modelling considers primarily the domain of rule-based behaviour. The *adaptive model* contains behavioural parameters of the individual pilot, when specifically differing from the normative model.

The analysis of pilot tasks in order to choose an adequate modelling formalism shows, that

- pilot tasks are *strongly concurrent* (e.g. maintaining altitude while reducing airspeed while communicating with ATC),
- processing of pilot tasks is driven by situation-dependent choices of different rule-domains (e.g. cruise navigation or approach navigation), this is a *choice between (excluding) alternatives*,
- the basic element within the considered task is always a *causal relation*, which can be formulated as production rule (if ... then),
- the situation space as well as the pilot's action space can be described by *discrete states* (e.g. flight segments, flaps settings) and *state transitions* (flight segment transition, flaps setting transition);.
- State transitions are driven by *discrete events* ("passing station X, reaching altitude Y").

Concerning these characteristics, *Petri nets* were chosen as most a backbone for knowledge representation purposes [26].

In current research the normative behaviour model as described above is being enhanced by providing information on the individual parameters. The aim is to achieve a *customized* model output in order

- to improve model accuracy,
- to cover areas of behaviour not yet described in the normative model and as a result
- to improve pilot acceptance.

A hybrid petri net/ CBR system is in progress using methods of example based reasoning to overcome particular shortcomings. [27]

A more recent approach uses a database of previously experienced *cases* as a repository for reusable solutions. Each case comprises an onset state, a target state and individual intermediate states and state transitions. During this *example based reasoning* approach *case retrieval* (or *initially match*) isolates those cases in the case base, that are considered to be compatible to the actual task. Emphasis is given on fast retrieval speed.

b) Intent and Error Recognition

Current theories, which are dealing with the human error process, are defining errors as a not complying with the given goals, and assume errors should be avoidable. Talking about a human error means the actor has done something which:

- was not intended,
- was not allowed by a prescribed set of rules or an external observer or
- led the task or system outside its acceptable limits.

The basic types of errors could be distinguished between a planning failure (mistake) and an execution failure (slip). A mistake is something the actor intended but which will result in a conflict in the future. Thus, a mistake is an incorrect decision or choice, or an error in deciding what is to be intended. A slip is defined as an action not complying with the actor's intention. The corresponding plan might have been good, but the execution was poor. In order to detect a mistake or slip intent-recognition of the actor is require. Moreover, detection of mistakes requires prediction of future actions. Thus the notion of intent and error are closely related.

Intent recognition applies machine intelligence for deriving the goals and subordinate actions of the human operator in the context of a complex situation. Intent recognition can support man-machine synergy by anticipating need for machine assistance without waiting for requests by the operator. For it, a problem solving system must be able to provide an interpretation of each situation. This interpretation is based on a set of rules of inference. The rule-based approach is commonly used for developing systems, which models human behaviour in well defined problem domains.

However, in many real life applications areas such as aerospace, decisions have to be taken based on inexact or uncertain knowledge. If decision makers are to be supported by computer systems, it is desirable that this type of knowledge can be represented. To cope with the problem of reasoning under uncertainty several methods like Bayesian inference or Dempster-Shafer theory have been developed.

Another approach is the classification by use of fuzzy logic to represent diagnostic knowledge. [28]. This comprises to:

- the evidence of a feature with respect to an error or intent hypothesis and
- the logical role of some information in confirming or rejecting an error or intent hypothesis.

The advantages of this approach are:

- universality of representation: all types of uncertainty can be modelled
- correspondence with human situation description
- compliance with human reasoning
- ease of understanding/manipulation
- adequacy of representation: the information is accurately modelled
- computational efficiency.

3.3.4 CASSY and CAMA

Intelligent assistant systems have been developed at the University of the German Armed Forces, Munich together with industry partners. The Cockpit Assistant **SY**stem **(CASSY)** for commercial aircraft under instrument flight rules in the ground-controlled airspace has already been flight tested successfully. At the time being, the newest development **CAMA** (**C**rew **A**ssitant **M**ilitary **A**ircraft) for military transport aircraft has reached the integration phase in the flight simulator facility of the University.

3.3.4.1 The Cockpit Assistant System CASSY

To comply with the discussed ideas a single, integrated avionic subsystem *CASSY* presents a possible solution for civil transport aircraft (**Figure 3.3-3**).

The **Automatic Flight Planner** module (AFP) generates a complete global flight plan [29]. On the basis of its knowledge of mission goal, ATC instructions, aircraft systems status and environmental data an optimized 3D/4D trajectory flight plan is calculated. The flight plan, or several plans, is presented as a proposal which the crew accepts or modifies. Once a flight plan is chosen it serves as a knowledge source for other *CASSY* modules. The AFP recognizes conflicts which may occur during the flight, e.g. due to changing environmental conditions or system failure, and appropriate replanning is initiated. If necessary, this replanning process includes the evaluation and selection of alternate airports. Since the module has access to ATC instructions, radar vectors are incorporated in the flight plan autonomously and the system estimates the probable flight plan.

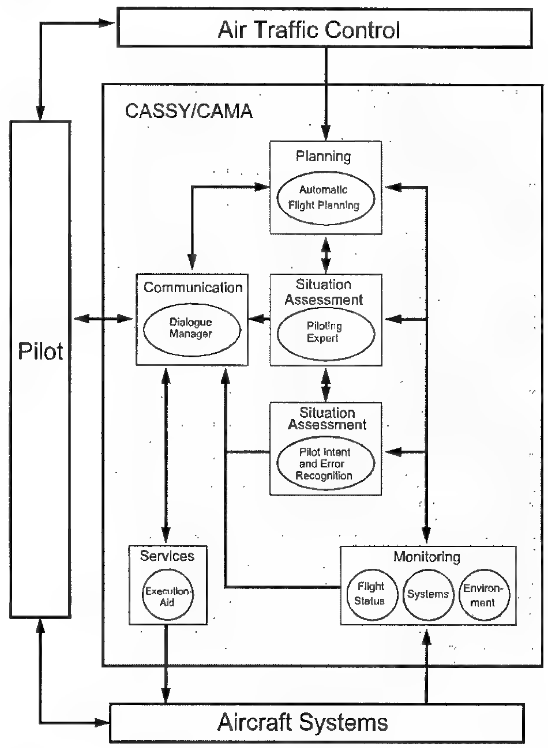


Figure 3.3-3 Core elements of the Cockpit Assistant System CASSY

The module **Piloting Expert** (PE) uses the valid flight plan to generate necessary crew actions. It is responsible for processing a crew behaviour model [26]. The normative model describes the deterministic pilot behaviour as it is published in pilot handbooks and air traffic regulations. The model refers to flight guidance procedures concerning altitude, speed, course and heading, but also to aircraft systems management. Given the flight plan and a pointer on the current leg, provided by the Monitoring of Flight Status, the system determines the appropriate normative values and tolerances on aircraft systems and flight status data.

In the module **Pilot Intent and Error Recognition** (PIER) [30] the expected crew actions are compared with the behaviour actually shown by the crew. The crew actions are derived indirectly by interpreting the aircraft data and pilot actions. If given tolerances from PE are violated, the crew will be informed by advice and warnings and detected mistakes are indicated to the pilots. In the case the crew deviates intentionally from the flight plan, the module checks if the behaviour fits to a given set of intent hypotheses which are also part of the crew model. These hypotheses represent behaviour patterns of pilots in certain cases, e.g. tasks to be done when commencing a missed approach procedure or to deviate from the flight plan to avoid a thunderstorm ahead. When an intentional flight plan deviation and the respective hypothesis is recognized, appropriate support, e.g. replanning is initiated.

Additional monitoring functions are needed to enable the system to recognize and interprete the current situation. The **Monitoring of Flight Status** provides the present flight state and progress. It is also able to report the achievements of the flight's sub-goals. The **Monitoring of Environment** gathers information of the surrounding traffic, e.g. from TCAS and of

weather conditions, also it incorporates a detailed navigational data base of the surrounding area. The health status of aircraft systems are monitored by the **Monitor of Systems** like a diagnosis system.

Communication plays an important role in *CASSY*. The kind of information to be transmitted in either direction varies with respect to the different modules. The information flow from *CASSY* to the crew and vice versa is controlled by the module **Dialogue Manager** (DM) [31]. The many different kinds of messages require a processing in order to use an appropriate display device and to present the message at the right time. As output devices both, a graphic/alphanumeric color display and speech synthesizer are used. Short warnings and hints are used to make the crew aware of a necessary and expected action and are transmitted verbally using the speech synthesizer. More complex information, e.g. the current flight plan, is depicted on a moving map on the graphic display.

Another important feature of the DM is that a priority ranking of the output message is evaluated and the most important message is issued first.

The input information flow is established by use of speech recognition in addition to conventional input mechanisms. In order to improve speech recognition performance, almost the complete knowledge of *CASSY* is used to provide situation-dependent syntaxes. Thus, the complexity of the overall language model is reduced significantly. The use of speech input and output devices also reflect the idea of human-centered development with respect to efficient communication.

In the module **Execution Aid** (EA) several functions like aircraft settings, navigation calculations and data base inquiries are realized and can be issued by the crew. These functions are similar to available automated functions in today's aircraft. For the pilots, the main difference is the use of speech input which facilitates the use of these services.

Results of the flight testing

After successful simulator tests, CASSY has undergone an eleven hours flight test program.

The modules of CASSY have been implemented in an off-the-shelf available Silicon Graphics Indigo workstation using the programming language C. A Marconi MR8 PC card was used as speaker-dependent, continuous speech recognition system. A DECTalk speech synthesizer served as speech output device using three different voices enabling the pilot to distinguish different levels of severity of messages. The components were connected using serial lines and ethernet.

The system was integrated into the test aircraft ATTAS (Advanced Technologies and Testing Aircraft) of the Deutsche Forschungsanstalt für Luft- und Raumfahrttechnik (DLR) in Braunschweig. The aircraft is well equipped for flight guidance experiments as it is possible to operate the aircraft via a single seat experimental cockpit located in the cabin. For testing typical IFR- scenarios, destinations such as the international airports Frankfurt, Hamburg and Hannover were chosen, starting from the home-base Braunschweig.

The experiments proved CASSY's functions throughout the complete flight from the take-off to landing. Speech recognition performed well in the aircraft as the surrounding noise was primarily engine noise which did not change much during flight. The recognition rates were similar to those achieved in the more quiet flight simulator environment at the University in Munich where CASSY was developed and tested prior to the flight test.

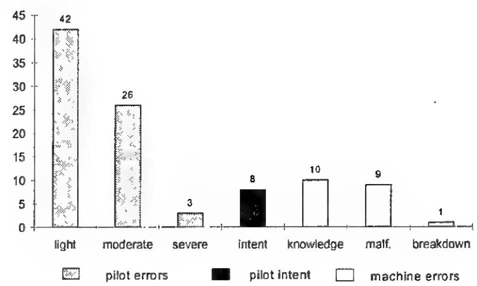
One important aspect of the tests was to prove the system in the high density air traffic in the near terminal area of German airports. During the campaign, any given ATC instruction could be processed and integrated into the flight plan by CASSY.

Pilot Errors were detected and the appropriate warnings were issued. System errors on the side of CASSY were uncritical in any case.

A total amount of 100 incidents leading to warnings have been evaluated to find out the reasons for the warnings and messages of similar purpose and the consequences they had. All incidents have been related to one of the three categories: pilot error, pilot intent and machine error (i.e CASSY errors in this case) (**Figure 3.3-4**).

In five cases of the intentional deviations from the flight plan the intention was autonomously figured out by the assistant system and the flight plan has been adapted, accordingly. In three cases the pilot had to inform CASSY about his intention.

Half of the machine errors were caused by an incomplete knowledge base, e.g. insufficient modelling of the aircraft performance and the other half by malfunctions of CASSY, i.e. software implementation errors due to less rigorous application of software development procedures. In one case such a malfunction led to a complete breakdown of the assistant system. In all machine error cases the pilot realized that a wrong warning was issued by CASSY. No negative influence on the pilot's situation assessment could be observed. In the one breakdown case, the complete CASSY system had to be restarted in flight, which took about 15 seconds. The only pilot input needed for such a recovery procedure is the flight destination. In all other machine error cases the warnings disappeared autonomously, when the incorrect assessed maneuver had been completed by the pilot.



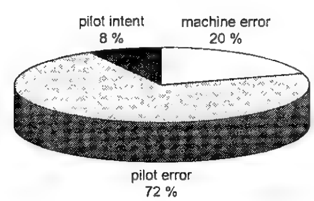


Figure 3.3-4 Error count during flight tests

Concerning the pilot errors the light errors are considered to result in an inaccurate or uneconomical, but safe maneuver. Moderate errors, probably would lead to a safety critical situation, and severe errors surely would lead to a dangerous safety hazard unless an immediate correction is made. All pilot errors, which occurred during the flight tests, were detected by CASSY. All moderate and severe errors as well as about 70% of the light errors were immediately corrected by the pilot after having received the warning or hint.

This means there were no significant negative consequences of errors or failures whether caused by the pilot or by CASSY. This is the symbiotic effect which is wanted!

Two pilots were flying with CASSY in the test aircraft. Additional pilots from Lufthansa German Airlines were sitting aside to observe the tests and assess the system's performances.

CASSY was well accepted by the pilots throughout the campaign. In particular, the pilots appreciated the autonomous flight plan function of CASSY. Warnings and hints were considered as justified and helpful. Speech input was generally used when complex inputs were to be made, e.g. frequency settings by using the name of the station instead of its frequency.

The experience with the Cockpit Assistant System *CASSY* in real IFR-flights have demonstrated this kind of system can cope with the real air traffic environment [32].

3.3.4.2 The Crew Assistant Military Aircraft CAMA

In future military transport aircraft, constraints created by low level flying in a high risk theater, the high rate of change of information and short reaction times will produce physiological and cognitive problems for the pilots. Low level flying over rapidly changing terrain elevation coupled with complex and dynamic tactical environment will result primarily in difficulties to maintain situation awareness.

With CAMA (*Crew Assistant Military Aircraft*) a novel approach breaks new ground to effectively enhance situation awareness in future military aircraft. This knowledge-based aiding system is being developed and tested in close cooperation between the DASA (Daimler-Benz Aerospace), DLR (German Aerospace Research Establishment), ESG (Elektronik- und Logistiksysteme GmbH) and the University of the German Armed Forces, Munich, based on the experience with CASSY. (**Figure 3.3-5**)

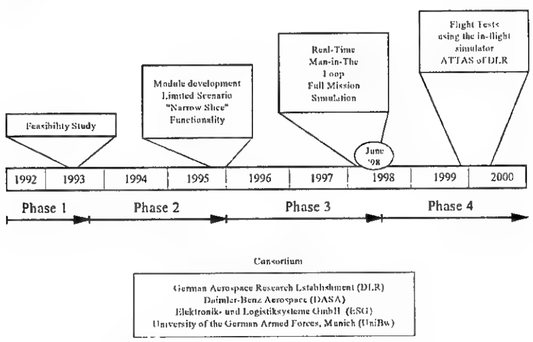


Figure 3.3-5 The CAMA Program

The CAMA-program was planned for four phases including a pre-contract feasibility study, a module development phase in a limited scenario for each module, and an integration phase with several testing steps. The actual integration phase will end in June 1998 with a man-in-the-loop full mission simulation campaign. After simulator tests the system will be demonstrated in flight experiments which are scheduled for winter 1999. It is planned, that CAMA will be integrated in the experimental cockpit of the ATTAS test aircraft of the German Aerospace Research Establishment (DLR).

CAMA assists the crew during a tactical mission to enhance situation awareness with an *interpretation of*:

- the altering tactical situation
- the actual weather situation
- the flight trajectory ahead to avoid safety critical ground proximity
- other safety relevant events

and through mission execution *services like*:

- an optimized 3D/4D trajectory flight plan
- time-management with regard to Time Over Targets (TOT)
- landing guidance without ground infrastructure
- evaluation and recommendation of alternates

Necessary *communication* with ground facilities like Command and Control Centers or Air Traffic Control (ATC) are provided by data link.

The overall *information flow* from *CAMA* to the crew and vice versa is controlled by the dialogue management.

As most important distinction from *CASSY, CAMA* takes the tactical situation into account.

The module **Tactical Situation Interpreter** (ESG) monitors tactical events and threat characteristics to analyze the transport mission situation. Threat data are assessed based upon digital terrain and elevation data (DTED) as well as the threat's models. The algorithm allows to calculate a position-dependent threat value taking terrain masking against the opponents radar into account. An internal *threat map* contains a complete representation of the tactical situation including field fortifications, SAM emplacements, lines of troops, fighter threat, hostile and own AWACS etc. [33].

The **Flight Situation and Threat Interpreter** module (UniBw) combines stored mission data with current or proposed plans and the results of the situation interpretation modules. Its main contribution is to find any plan-conflicts and to initiate a conflict-solving process.

The **Mission Planner** (UniBw) creates and maintains a take-off-to-landing mission flight plan, including routes, profiles, time- and fuel-planning based on knowledge about the mission plan, gaming area, destination, ATC instruction, aircraft status, environmental data, etc.. Events like failures of aircraft systems, weather or threat changes and ATC or C&C instruction and information are taken into consideration. The mission planer covers the flight under Instrument Flight Rules (IFR) as well as tactical routing. Time management, especially with regard to a TOT (time over target), fuel calculations and routes/profiles calculations will assist the crew. The calculated trajectory is presented as proposal to be accepted or modified and serves as knowledge source for other function blocks.

The **Low Altitude Planner** (ESG) calculates the trajectory based on knowledge about weapon and system capabilities. Minimum risk routes are chosen to bypass hostile defenses.

Based on the aforementioned *threat map* the LAP generates an optimized low level flight plan by calculation of a minimum risk route through the gaming area. In generating plans, account is taken to the current situation and available resources, such as fuel or time, while complying with waypoint restrictions and other mission constraints [33].

The module **Terrain Interpreter** (DASA) contains a digital terrain data base to warn the cockpit crew if the projected aircraft path is getting too close to the ground or an obstacle. This eliminates several traps such as controlled flight into terrain or descend into ground short of the runway.

The aircraft may need to be updated with fresh information during the mission. The **External Communication Interface** (DASA) will provide the crew and assistant system with external data, like weather forecasts, the intention of external war-fighting units or changed tactical situations that might effect the planned mission.

The module **System Interpreter** (DLR) monitors and analyses on-board systems to determine the current state of the aircraft systems. Any detected malfunction is evaluated to determine the degree of degradation of the overall system capability.

The module **Computer Vision External** (UniBw) will assist the crew by computer vision during the approach phase to avoid collisions in high density air traffic and to ensure a quasi ILS/MLS landing at any unequipped landing field. To improve the aircraft state estimation, a camera-system will be used to determine the relative position to the runway. Two cameras with different focal lengths are used in parallel for bifocal vision. A wide-angle lens is used for initialization and stabilization and the tele-lens for object tracking. The system has been tested in real-time with a hardware-in-the-loop simulation. Image processing combined with the current inertial sensors are able to perform precise landing guidance. [34]

To improve the reasoning capability pilot model, the eye movement of the pilots will be evaluated. With the module **Computer Vision Internal** (UniBw) a camera system similar to the hardware configuration of the module Computer Vision External is used to register head and eye movements of the aircrew. This information, for instance the moving line of sight to a control surface or to a special indicator, could be used to confirm the need for a warning or a hint. The measurement is remote.

The **Pilot Behavior Reference** (UniBw) module describes a rule-based model of expected pilot-behavior concerning the actual flight plan and the module **Pilot Intent and Error Recognition** (UniBw) evaluates the pilot's activities and mission events in order to interpret and understand the pilot's actions like presented in chapter 4.
The information flow from the machine to the crew and vice versa is controlled exclusively by the module **Dialogue Manager** (UniBw) [31] which corresponds to the CASSY dialogue-management (see above) [31]. A substantial innovation is a Horizontal Situation Display. The Horizontal Situation Display is an interactive touch-sensitive map display organised in a number of layers which allows the crew to optionally select from several map-presentations in any combination. It allows to depict tactical and threat information as well as a variety of navigational elements and a topographical map similar to the currently used low flying charts paper-maps. A second alpha-numerical display contains the flight-log and is used for in-flight departure-, approach- or missed-approach-briefings.

3.4 Computer Oriented Metering Planning and Advisory System (COMPAS)

3.4.1 Overview[1]

The objective of Air Traffic Control/Air Traffic Management is to ensure safe, efficient and timely operations of a large number of aircraft using the same airspace at the same time. A pilot of an individual aircraft generally has very little knowledge about and no control of the other traffic. Consequently an independent, ground-based authority, i.e. Air Traffic Control (ATC), has been established to coordinate and control all traffic operations in a given air space.
Air traffic control can be considered as a work system where human operators make use of a variety of ground-based and on-board sensor systems to collect information. Similarly, they use different ground-based and, largely through the pilot on-board, effector systems to implement their intentions and commands. However, most, if not all, processing functions are currently still carried out in the brains of human controllers. In many high density traffic areas the human control capacity has already become the limiting factor in the overall system performance of the ATC system. In order to cope with future increased air traffic demand and to overcome the limitations of the human information processing capabilities, more and more of the information processing functions of the human ATC controllers must be supported by or even replaced by intelligent machine functions.
The COMPAS system [35-40] which is described in this section is an example of the successful introduction of knowledge-based planning support in air traffic control. COMPAS is a planning tool to assist the controller in the handling of arrival flights in the extended terminal area of major airports. It aims at improving the flow of traffic and the efficient use of the available airport landing capacity while reducing planning and coordination effort of ATC personnel. The system has reduced controller workload of the approach controller team and does not cause any significant additional load to the en-route controller teams.
Main basic functions of the system are monitoring and diagnosis of the traffic situation based upon the on-line input of the initial flight plans, actual radar data and the actual wind. Basic planning parameters such as: aircraft performance data, air-space structure, approach procedures and controller strategies, separation standards and wind models are already stored in the computer and do not require additional inputs by the controller.

[1] The presentation in the section 3.4 follows the description of COMPAS in [7]

Each time a new aircraft enters the predefined planning area, COMPAS determines the optimal sequence of all approaching aircraft and calculates a schedule of arrival times for the "Metering Fix", a waypoint at the Terminal Maneuvering Area (TMA) boundary and the "Approach Gate", a waypoint on the runway centerline. The computer-derived optimum sequence and schedule and some advisories on achieving the desired plan are displayed to all controller teams who are responsible for the control of the inbound traffic. Each of these teams receives only those data which are necessary to control the arriving flights in its sector and to contribute to the optimized overall plan. Usually there is no interaction required between COMPAS and the human operator. However, the controller has the ability, if he sees the need, to modify the computer generated plan or to change planning parameters and constraints through a small function keyboard.

3.4.2 Arrival Planning at Airports

The generic, top-level functional structure introduced in section 2.3 can be applied to *arrival sequencing and scheduling* as illustrated in **Figure 3.4-1**.

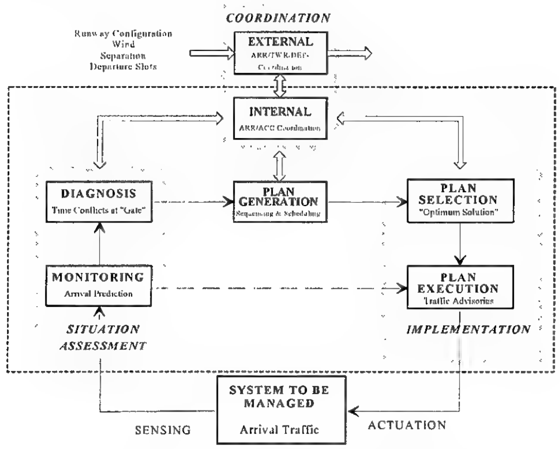


Figure 3.4-1 Generic Structure of Arrival Sequencing and Scheduling Functions

Figure 3.4-1 illustrates the arrival sequencing and scheduling functions as part of the short-term-planning layer of ATM/ATC. At this level, the system-to be controlled is the actual air traffic, a set of inbound aircraft. Their flight plans, positions, altitudes and identifications are continuously sent from different sensor systems to the situation assessment function. Here, headings, tracks, speeds, descent profiles etc. are continuously calculated and sent to the diagnosis function. The diagnosis function predicts, extrapolates and correlates future trajectories to detect deviations from the plan and to detect potential future conflicts. If a planning conflict has been found, the plan generation function is activated. It attempts to resolve the conflict by using stored solutions or stored problem solving methods. The plan generation results represent tentative solutions for the sequence, schedule and trajectories for the inbound flights. These planned and still tentative solutions must be coordinated with other planning agents (e.g., adjacent upstream ATC-sectors, the downstream tower sector, with departure control). After an agreement has been reached through coordination, the potential solutions are transferred for implementation. Here they are evaluated and the "best" solution with respect to a given goal criterion is selected. The solution is executed by the plan execution function which transforms the solution (sequence, schedule, trajectory) into commands (heading, speed, descent, intercept etc.) which are transmitted to the systems-to-be-controlled: the arriving aircraft.

Some of these functions can have the potential for being implemented by an intelligent computerized planning system to support the human opèrator in the control of arrival traffic. In COMPAS, the monitoring, diagnosis, and planning functions are performed automatically and continuously by the computer. The results, the *COMPAS plan*, are presented through a specially designed Human-Computer-Interface (HMI) to the human operator. The human controller can integrate the COMPAS generated plan into his other control activities and retains the ultimate authority for decision making and implementation. He is also able to interact with the computerized planning function through the HMI.

3.4.3 Monitoring, Diagnosis and Planning Functions

The whole process is divided into several steps:

- the acquisition and extraction of radar and flight plan data (**Monitoring**)
- the prediction of the flight profile and the calculation of the arrival times (ETO) as if the aircraft were alone in the system, checking for time-conflicts at the so-called "Gate" (**Diagnosis**)
- planning of the optimal overall sequence and calculation of the planned arrival times with minimum total delay for all known inbound flights (**Planning**)
- freezing of the planning status when the aircraft reaches its top of descent.

There are several assumptions within the flight profile model with regard to an economical descent profile and the performance of the type of aircraft. A simplified method based on airline operations data was developed for profile prediction. The different profile legs are calculated with the actual radar position, airspeed, flight plan data, altitude, wind data as received on-line from the ATC data processing system. Further consideration is given to the aircraft type-specific economical descent gradient, minimum cost descent speed, the aircraft deceleration rate and possible air traffic constraints at the Metering Fix and the Approach Gate. The estimated time of arrival (ETO) is based on the preferential flight profile of the aircraft. The earliest estimated time of arrival (EETO) takes into account all measures to advance the aircraft within its performance envelope without requiring any thrust increase. The time difference between ETO and EETO is used as a margin for sequence changes to maximize traffic throughput without violating economical flight conditions.

With its EETO, the newly entering aircraft is inserted into the already existing sequence (see **Figure 3.4-2**) The result is an initial plan, i.e., a tentative sequence of aircraft according to the 'first-come-first-served' principle, but possibly with still unresolved time-conflicts.

As an example of the knowledge-based core functions in COMPAS, the planning algorithm to establish the optimal sequence and schedule shall be described briefly. It is an analytical 'Branch-and-Bound' algorithm with three major elements.

- merging of new arrivals into the sequence
- time conflict detection and
- time conflict resolution with optimization criteria.

The overall goal here is to minimize the total delay time by optimal combination of the aircraft of different weight classes. A dense sequence of aircraft (i.e., minimum total delay) contributes to the best utilization of the available runway capacity. The algorithm can be graphically represented as an heuristically oriented search in a decision tree. The nodes represent the individual sequence pairs which are characterized by the earliest time conflict between two aircraft in each case.

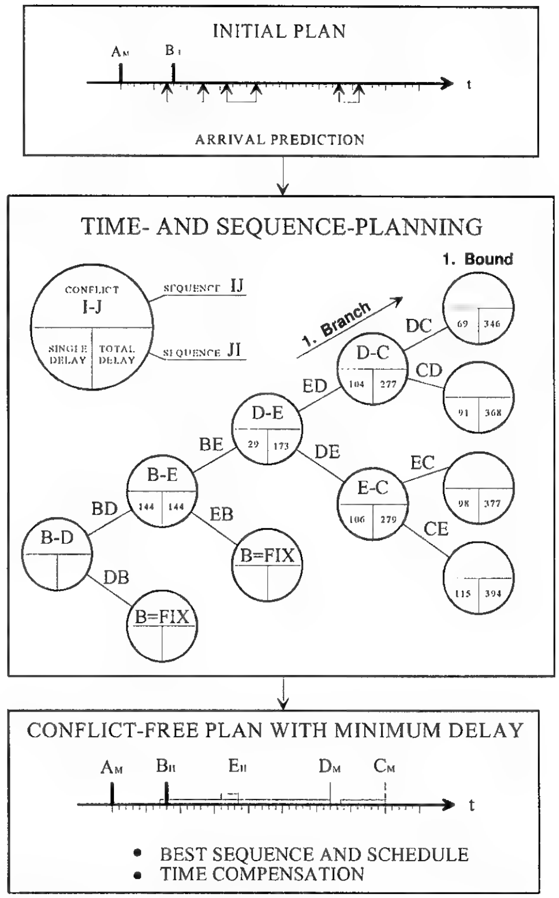


Figure 3.4-2 COMPAS Planning Algorithm

The branches show the alternatives for conflict resolution and the decision tree is developed following the principle 'solve-the-earliest-conflict-first'. The cost function is the total delay time, which is accumulated until a conflict free plan is found. The cost value of this first solution is called 'first bound' (usually it is a sub-optimal sequence). A backtracking procedure leads sequentially to all those nodes with less then the total delay of the first bound. From there new branches in the search tree are developed. The development of a new branch will be stopped either when the total delay value of the 'first bound` is exceeded or it leads to a new bound with less total delay. The planning process ends when all remaining conflicts have been resolved. The result is a sequence for all known inbound flights with the shortest time separation between any preceding and trailing aircraft equal or greater than minimum permitted separation and a planned delivery time for all arrivals at the so-called "approach gate". From this "gate time" all other intermediate arrival times for other waypoints are calculated individually for each actual flight. Furthermore, an advisory is calculated which defines how much each arrival has to be advanced or delayed.

3.4.4 Man-Machine Interaction

The layout of the man-machine interface of COMPAS was of crucial importance to the acceptance of the whole planning system. "Keep the controller in the loop". "Give him the plan, but leave the implementation to his experience, skill and flexibility". "Minimize the need for keyboard entries and keep the advisories as simple as possible". These were the main guidelines and principles for the design of the Human-Computer interface, i.e. the COMPAS-display and the COMPAS-keyboard.

Figure 3.4-3 shows the cooperation between human and computer-based functions for the COMPAS system.

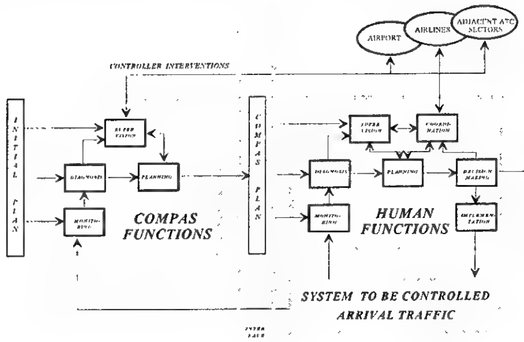


Figure 3.4-3 Man-Machine Interactions in COMPAS

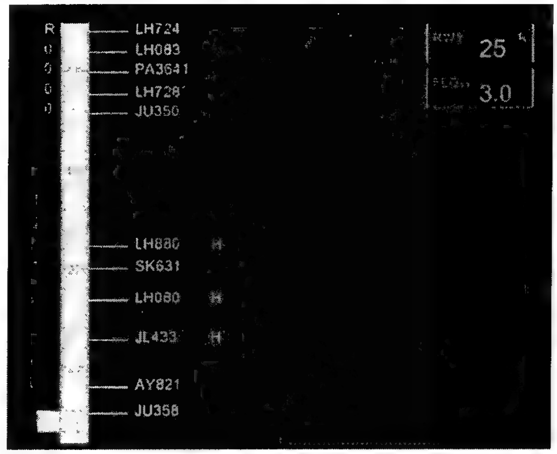


Figure 3.4-4 COMPAS Enroute Controller Display

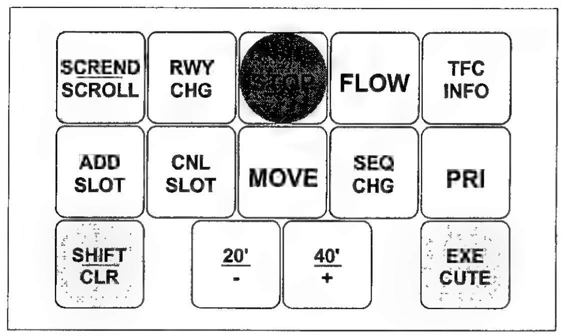


Figure 3.4-5 COMPAS Keyboard

3.4.4.1 Display

The display of the solutions from sequencing and scheduling is specially tailored to the needs of the different ATC units (Enroute and Approach) which are involved in the handling of inbound traffic. **Figure 3.4-4** shows the features of the controller display. The planned aircraft in the arrival flow are listed sequentially in a vertical time line, with the earliest arrival at the bottom. The aircraft labels are additionally marked with 'H' or 'L' according to the weight categories of the individual aircraft (H=HEAVY, L=LIGHT, the standard MEDIUM category is not indicated explicitly). The vertical position of each arrival is correlated with a vertical time line which moves downward with the progress of time. The bottom of the line represents the planned time over the Metering Fix (enroute display) or Approach Gate (approach display). A color code is used to indicate from which approach sector the aircraft are coming. The letters left of the time line give a rough indication (advisory) of the suggested control action for each aircraft during the descent phase. Four characters are defined in order to reach the planned arrival time and to establish a dense, smooth traffic flow ('X'= an acceleration of up to two minutes, '0'= no action, 'R'= a delay of up to four minutes and 'H' = more than four minutes delay). The controller is free to accept or to reject the advisory. He can modify the computer-generated sequencing plan if he desires or if unforeseen events have occurred.

In addition the display shows, at top right, two basic parameters for information: the active runway direction (e.g. 25) and the so-called "FLOW", which actually tells the minimum permitted and planned separation.

The controller can move a cursor up or down on the time line to identify a specific aircraft or time window if he wants to enter modifications.

3.4.4.2 Keyboard

Figure 3.4-5 shows the intentionally very simple functional keyboard for controller-computer interaction. There are ten function keys to change the basic parameters or operational functions.

Inputs to modify the basic planning parameters can only be entered by the approach controller, i.e.:

- change of minimum separation (FLOW),
- change of landing direction (RWY CHG) and
- STOP in case of closure of runways.

Inputs to modify the automatically generated sequence and schedule can be entered at all controller keyboards, both in the in enroute and approach sectors, i.e.:

- insertion of arrivals unknown to the system into sequence (ADD SLOT),
- cancellation of planned arrivals (CNL SLOT),
- move an arrival over several positions in the sequence (MOVE),
- change of planned sequence between two successive aircraft (SEQ CHG),
- assign priority to an arrival(e.g. emergency, ambulance, etc.)(PRI)
- display of additional information to the en-route controller (TFC INFO), to give additional information about aircraft in adjacent sectors.

3.4.5 Successful Implementation of COMPAS at Frankfurt Airport

The COMPAS-system was installed in the Frankfurt/Main Air Traffic Control Center of DFS, the German Air Traffic Services in 1989. Since then it has been used successfully, 24-hours-a-day, and has shown improved traffic flow and throughput. It has found overwhelming acceptance with the human operators. As scientific, statistically proven studies have shown, this is mainly due to the planning results which are generated by the knowledge-based functions. They are reasonable, feasible and easy to comprehend and to apply. Controllers feel that these advisories are "non-intrusive", and give an easy-to-follow framework plan while allowing them to stay in the loop with some flexibility to make changes. Above all, the controllers

retain the ultimate authority and responsibility. Results of the field evaluations can be found in Reference [40].
The present development of COMPAS is focused on two main directions:

- Incorporation of more sophisticated models, advanced planning technologies and heuristic planning methods.
- Full integration with other planning support tools for ATC Terminal Automation, (e.g.: 4D-Planning; Wake Vortex Warning System; Arrival/Departure Coordination; Airport Surface Traffic Management).

This will be achieved through the application of advanced knowledge-based technologies (e.g.: Multi-Agent Planning; Hierarchical Planning; Multi Sensor Data Fusion; Information Management).

4 COMPLEX AND DISTRIBUTED DECISION MAKING

In the chapter 3 several examples of intelligent decision aids for human operators have been discussed. APES, Copilot Electronique, CASSY and CAMA are systems which support the functions of a pilot in the cockpit of military or civilian aircraft (see Figures 3.1-1, 3.2-3 and 3.3-3). They can be considered as work systems (see Figure 2.2-1) where the decision aid has the role of the *tool*, and the aircraft is the *work object*.
In the case of COMPAS the situation is more complex: This system supports more than 10 different air traffic controller working positions, each of which controls a different part of the airspace around an airport. (The Figure 3.4-3 shows the lay-out for only one working position.) The decision making process is distributed in this case among the various controllers and the COMPAS system in a cooperative workshare. This raises the question, how the *functional architecture* of such complex and distributed decision making systems can be modelled.

4.1 Networks of Coupled Work Systems

In chapter 2 the functional architecture of work systems which are managing aerospace systems was described (Figure 2.3-1). The coordination function of this architecture provides the possibility of coupling different work systems with each other (see also [7]). In this chapter, networks of coupled work systems will be used to model complex and distributed management processes, like air traffic management and command and control. **Figure 4.1-1** shows the principle.

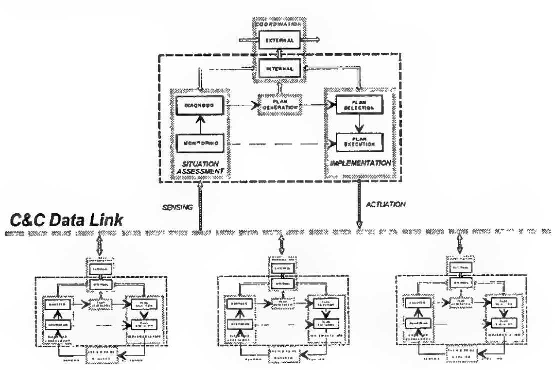


Figure 4.1-1 Hierarchical System of Coupled Work Processes

In this Figure four work systems are coupled through a data link. The three lower ones are using the data link for the *coordination* of their management functions. Each of them is dedicated to the management of a particular „system". The coordination can be organised in different forms: Exchange of data (e.g. the plans), negotiations about the plans, setting constraints for the planning processes of the other work systems, etc. The upper work system is „managing" the three lower ones, employing its sensing and actuation functions. This principle of coupling is called *hierarchical*.
The principle of coupled work systems will be illustrated by some examples in the following sections.

4.2 Air Traffic Management (ATM)

4.2.1 Distributed Decision Making in ATM

Air Traffic Management (ATM) is a good example for complex and distributed decision making:

- ATM is a very large scale system in terms of both time and space. The temporal scope is from long-term to the very immediate short-term. The spatial scope is from global to local. A broad variety of functions of different detail and character must be carried out in parallel at different levels, distributed over different time horizons and at different locations. Still, all information processing is interrelated and has to be coupled in numerous control loops.
- Most of the planning and control functions in ATM are highly complex. Many different requirements and constraints originating from airport operators, from airline operators, from pilots and from the environment (noise, pollution avoidance), which very often have competing or even contradicting goals, must be considered simultaneously. Some functions must be performed cooperatively between on-board and ground-based systems. Other ground-based functions and tasks are divided and allocated or shared among several different ground units.
- Despite of the application of the most advanced sensor technologies and data processing capabilities in ATM, it remains a significant challenge for planning and control functions to adapt continuously to changing conditions, i.e., to close all loops in real time. As ATM is, in principle, largely a customer service system, it must comply with airline, pilot, passenger, and airport needs. Unforeseen events, disturbances, and changing priorities are commonplace and occur on short-notice. Weather (headwinds, fog, thunderstorms, etc.) frequently add to the problems of uncertainty in ATM-planning and control.
- It is unlikely that in the foreseeable future there will be aircraft flying automatically without a pilot on-board, in airspace being automatically controlled without controllers on the ground. Thus, there will still be pilots and controllers in charge and responsible for the conduct of air traffic. Human limits in perception and information processing and the typical human approaches to planning and decision making (heuristic, holistic) all impose severe challenges on the designers of planning and decision support systems, who must model and transfer human cognitive processes to intelligent machines. Only when both the representation of information and the manner of dialogue and interaction with an intelligent device are acceptable to the human operator, will knowledge-based functions be successfully implemented, no matter how intelligent and advanced they may be.

4.2.2 Functional Decomposition of ATM

Advanced operational concepts for ATM are presently under development in the USA (AAS [41]) and in Europe (EATMS [42]; CATMAC [43]). They follow a well designed, consistent architecture in which all ATM functions are deliberately coupled and performed by several autonomous, but cooperating planning agents. For example, in the german CATMAC (Cooperative Air Traffic Management Concept) proposal, the functions are decomposed:

(1) In terms of time: -> strategic/long-term
-> tactical/medium-term
-> short-term planning
-> actual control
(2) In terms of space: -> global

-> continental
-> regional
-> local.

The ATM functions range from the very broad, high level strategic planning functions many months in advance of an actual flight, down to the very specific sub-tasks, e.g., resolving within seconds short term conflicts between two aircraft.
In [44] the generic structure of the future ATM system has been discussed and is shown in the **Figure 4.2-1**.

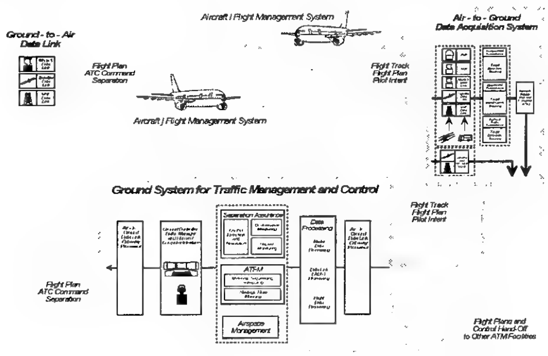


Figure 4.2-1 Generic Structure of the Air Traffic Management Function

This Figure illustrates the complexity of the functions needed to guarantee the safe and efficient flight of aircraft in a piece of airspace. The *ground-based system for traffic management and control* shows the infrastructure necessary to carry out the functions of separation assurance, air traffic flow management (ATFM) and airspace management. The ground-based system communicates with the on-board *flight management system* through a *ground-to-air data link* and *an air-to-ground data acquisition system*, using the same data link. The overall system can be considered as a network of coupled control loops with different time constants. Separation assurance has a time constant in the order of minutes or hours, ATFM in the order of hours or days, and airspace management in the order of days or even years.
The ground system in the Figure 4.2-1 serves a certain airspace. The functions of separation assurance, ATFM and airspace management have to be provided also in the adjacent airspaces. For this purpose the ground systems are coupled through data buses and voice communication systems. This creates a network of ground systems, which can be modelled as a system of coupled work systems. This principle will be explained with the example of COMPAS.

4.2.3 Example: Distributed Planning in COMPAS

The COMPAS system has been described in the chapter 3.4. It provides an optimal plan for the sequencing and scheduling of all aircraft arriving at the airport of Frankfurt. The airspace which is used by these aircraft is controlled by more than 10 different controller working positions. The COMPAS plan is transmitted through a data bus to each of these positions, providing the controllers with those segments of the plan which corresponds to their airspace. The controllers can interact with the planning process using the COMPAS keyboard. This is shown schematically in the **Figure 4.2-2.**
This Figure describes a network of individual work systems (for the Sectors 1, 2 and 3), which are coupled through a common plan for the sequencing and scheduling of the aircraft under the control of these work systems. In this Figure the COMPAS system can be regarded as a fully automatic work system, which *cooperates* with the individual air traffic controller working positions (coordination in a hierarchical system).

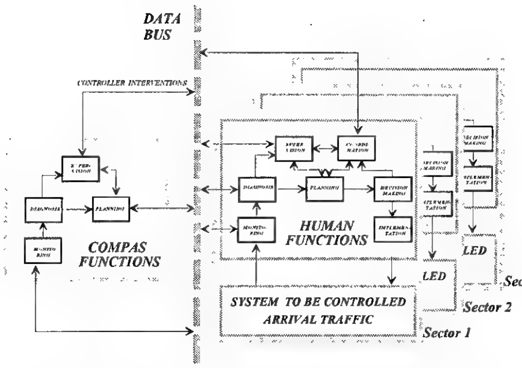


Figure 4.2-2 COMPAS as a System of Coupled Work Processes

4.3 Command and Control (C&C)

4.3.1 Functional Decomposition of C&C

The structure of C&C processes is the subject of many research projects and studies (see e.g. [45]). The generic structure of a command and control loop is described in **Figure 4.3-1.**

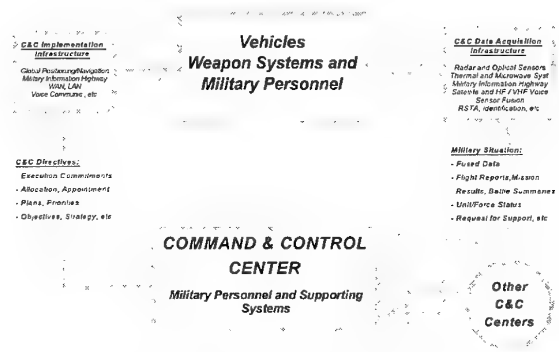


Figure 4.3-1 Generic Structure of the Command and Control Function

In a complex combat scenario, this loop exists for different command levels and temporal horizons (see [46]). **Figure 4.3-2** shows the order of magnitude of the time constants of the C&C loops on the unit, force, component and theater levels.
The application of the concept of coupled work systems to command and control loops will be illustrated by the examples of *distributed mission planning* for military aircraft and *air operations.* These examples are discussed in more detail in [7].

COMMAND & CONTROL LOOPS

Unit or Weapon System Level	*(< 1 h)*
Force Level	*(< 4 h)*
Component Level	*(< 24 h)*
Theater/Joint Force Level	*(< 48 h)*

Figure 4.3-2 Time Constants of the Command and Control Loops

4.3.2 *Example: Distributed Mission Planning for Aircraft*

For the on-board planning problem of a highly automated (potentially autonomous) air vehicle, mission and trajectory plans are developed within the military hierarchy to optimize an established objective function (e.g., minimize fuel, minimize time or maximize a mission-specific measure of accomplishment) subject to specified constraints (e.g., allocations on mission timelines, fuel, flight safety, etc.). A typical hierarchical decomposition of the mission planning problem is one wherein skeletal plans of the entire mission are constructed at the highest level, the *mission level.* The skeletal mission level plan must be generated in sufficient detail to ensure that on-board resources are sufficient to achieve the planned objectives and that timeline and survivability constraints are honored. At intermediate levels, the *route/activity levels,* near-term actions that are consistent with the mission level plan are planned in greater detail. Finally, at the lowest level of the hierarchy, the *flight safety level,* very near term commands are generated for sensor and control systems in a manner that ensures flight safety.

Figure 4.2-3 in the section 4.1 can be regarded as a two level decomposition of such a planning problem for three military aircraft (e.g. Unmanned Tactical Aircraft) which operate in the same airspace at the same time. The work system in the upper level creates skeletal mission plans spanning the entire mission of all three aircraft, and the 3 work systems in the lower level fill in the details of trajectory and payload activities that are required in the near term in pursuit of the mission plan of each individual aircraft.

The network of coupled work systems in the Figure 4.2-3 can be layed out as a *command system*, where the upper work system imposes mission plans to the individual aircraft; or as a *cooperative system* (distributed hierarchical and coordinated decision making); or as a mixture of both features, by the appropriate layout of the coordination function of the work systems.

4.3.3 *Example: Functional Model of Air Operations*

Military air operations are essentially plan oriented. At all levels from commander to combatant and in all domains, planning is the fundamental organizing principle and is the key to solving problems in combat. Thus, a planning paradigm is a "natural" representation of the full scope of military air operations. Such a paradigm is adopted here to provide a framework for a discussion of command and control functions in military air operations and to illustrate functional relationships between military air operations at levels ranging from theater to battlefield to individual missions.

The military notion of a "plan" evolves from a process that includes: (1) situation analysis; (2) determination of objectives; and, (3) selection of a course of action intended to realize the objectives. The process is viewed as iterative along a temporal axis and recursive at finer levels of detail across the hierarchical command. Thus, the generation of a plan at the highest level ("campaign") invokes the formulation of subordinate plans through a similar process at lower levels, in order to meet goals implicit in the planned courses of campaign level action. For example at the campaign level, a course of action is selected that calls for the defeat of enemy fielded forces. This course of action implies an objective to gain air superiority over enemy territory. That objective then generates a course of action indicating a sequence of combat actions against enemy air defenses. The objectives of these actions then define aircraft missions in the daily battle plan. Mission objectives finally result in the selection of targets for individual aircraft and mission plans are then crafted to create a desired effect on the targets. Thus, consistency of objectives across levels and coordination at every level in the command structure is effected, largely through the inheritance of plan objectives. The intermediate levels in the command hierarchy exist primarily to provide insight at the appropriate scope into important operational detail.

From this perspective, military air operations may be conveniently mapped onto the functional model of coupled work systems developed in this chapter. **Figure 4.3-3** shows this example.

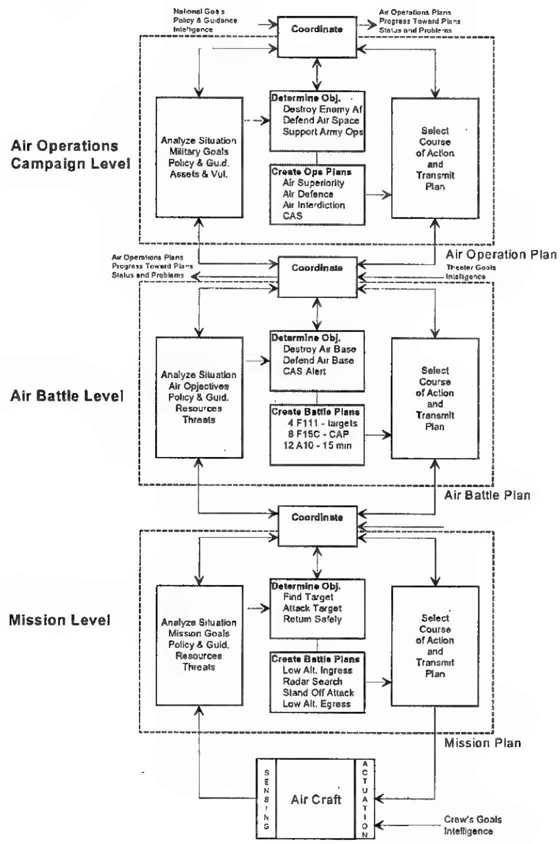


Figure 4.3-3 Functional Model of Air Operations

Thus, if we examine the model at the Senior Officer's level, the system under control is the command and control system for the theater. At a command center level, the system under control is the collection of assets that constitutes the force committed to battle. For combatants, the system to be controlled then, is the aircraft or weapons system at their command.

5 CONCLUSION

A functional analysis of human decision making has shown, that the concept of work systems is very helpful for the understanding and modelling of man-machine interactions in management tasks. Several sucessful examples of decision aids which have been developed in the USA, in France and in Germany were discussed in detail. They illustrate the design, development and evaluation of intelligent decision aids for the support of human operators.

In several of these examples, the decision process was concentrated upon one work system, the cockpit of an aircraft. In more complex functions, like air traffic management or command and control, the decision making process can be distributed in space and in time, so that several decision makers are taking part in the decision, at different times and/or locations. The concept of coupled work systems can be used to model these distributed decision making processes. Several examples were discussed to explain, how the principle of coupling elementary work systems can be applied to the design

of intelligent decision aids in such cases. The appropriate layout of the coupling mechanism allows the representation of command as well as cooperative structures.

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Technology Requirement to Implement Improved Situation Awareness: Machine Perception

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1. ABSTRACT

Situation awareness is the ability of an unmanned vehicle intelligent control system to model the world. A world model is an intelligent system's current internal estimate of the state of the world, plus its prior knowledge of the history of the world, plus knowledge about the rules of physics and mathematics, plus rules of behavior, task skills, and basic values. World modeling is the ability of the intelligent system to maintain and use a world model to predict and filter sensory experience, to understand the past, and to simulate the future. Perception is the functional transformation of data from sensors into situational awareness.

The technology required for machine perception exists. The ability to design machine perception systems with the sophistication and quality to be useful to field commanders is within reach.

2. PREFACE

Perception and situation awareness are processes that occur naturally in the human mind. In order to discuss these concepts in terms of technology requirements that can be implemented by machines, we make the following operational definitions:

Df: perception ::= the transformation of sensor signals into knowledge about situations and events in the world.

Df: knowledge ::= data structures and information that define the intelligent system's world model

Df: situation ::= a set of relationships that exist between entities in the world

Df: situation awareness ::= correspondence between knowledge in the system's world model and a situation in the world

When a system has situation awareness, it can take appropriate action.

Perception occurs as a result of the interactions between three functional elements: sensory processing, world modeling, and value judgment.

2.1 Sensory processing

Df: sensory processing ::= a process by which sensory data interacts with prior knowledge in order to recognize and track objects and situations, and generate and maintain useful internal representations of the world.

Sensory processing consists of five basic functions:

1) Windowing (or its inverse, masking) selects the regions of space and/or time to be considered. The shape, position, and duration of spatial and temporal windows are determined by the shape, position, and duration of regions in an image (or collection of sensors), or in the world, that are labeled as worthy of attention. Regions may be worthy of attention either because they are goal related, or because they exhibit properties that are unexpected or dangerous, or because they are otherwise noteworthy. The size and shape of each window is determined by the size, shape, and level of confidence in the position and motion of the entity defining the window.

2) Grouping integrates or organizes spatially and temporally contiguous subentities with similar attributes into entities. The grouping process segments, or partitions, an image into topological regions with entity labels, or names. Any particular grouping is a hypothesis based on gestalt heuristics. A grouping hypothesis is confirmed or rejected based on the usefulness of the hypothesis in predicting sensory input.

3) Computation calculates observed entity attribute values generated by the grouping hypothesis.

4) Filtering (e.g. by recursive estimation) computes a best estimate (over a window of space and time) of entity attribute values based on correlation and differences between predicted and observed entity attribute values. Filtering

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also computes statistical properties such as confidence in estimated attribute values.

5) Recognition (classification, or detection) establishes a correlation or match between estimated attributes of entities observed in the world and attributes of entity classes stored in the system's knowledge database. Topological, generic, and specific entity classes may be stored in the knowledge database, and observed entities may be recognized as belonging to topological, generic, and/or specific object classes.

2.2 World Modeling

Df: world modeling ::= a process that constructs, maintains, and uses a world model to predict sensory inputs and simulate behavioral plans.

Df: world model ::= an estimate of the state of the world,
plus knowledge of the history of the world,
plus knowledge about the rules of physics and mathematics that govern how the world works,
plus rules of behavior for external agents in the world,
plus task skills that describe how internal agents should act so as to accomplish goals,
plus values that define
what is good and bad,
what is valuable and worthless,
what is important and unimportant,
and what is the level of confidence that can be attached to any part of the world model.

2.3 Value Judgment

Df: value judgment ::= a process that:
a) computes cost, risk, and benefit of actions and plans,
b) estimates the importance and value of objects, events, and situations,
c) assesses the reliability of information,
d) calculates the rewarding or punishing effects of perceived states and events.

Value judgment is a set of cost/benefit functions that determine how much priority an intelligent system should assign to tasks and goals, and what worth should be assigned to objects, agents, relationships, or regions of space. Value judgment calculates how rewarding or punishing specific actions and events are or can be expected to be. Value judgment also computes statistics on how well observations correlate with expectations, and assigns uncertainty factors to all entities and attributes stored in the world model.

2.4 Knowledge

The world model contains knowledge about the world. Knowledge is represented in data structures in the form of state variables, attributes, entity frames, event frames, relationships, images, maps, rules, equations, and recipes. State variables define estimated conditions in the world. Attributes describe properties. Entities and events can be represented in frames that contain lists of state variables, attributes, and relationships. Images contain information about the position of entities in the world, and maps give an overhead view of the terrain overlaid with labels, icons, and text that provide information necessary for situation assessment and planning of action.

Representation is important both for the machine system and for the human operator. Maps provide information about the battlefield. Where are the friendly and enemy forces? Where is the high ground? Where are the roads, the rivers, the barriers to movement?

Images are windows into the world from the viewpoint of a sensor. It is important to know where the sensor is located and where observed entities are relative to the sensor viewpoint. Images are also important for display of situations to the human user. The user should be able to choose a viewpoint that is optimal to the user's purpose. This typically requires specification of scale (or resolution) and range (or field of view). For high-level observation and planning, maps with a range of many kilometers and resolution of 30 meters may be optimal. For tactical observations and planning, maps with a range of about a kilometer with resolution of 3 meters may be needed. For individual units to maneuver through the environment, images with both a wide and a narrow field of view are required. Resolution in the wide field of view can be around 0.5 degree per pixel, whereas in the narrow field of view, resolution of about 0.02 degrees per pixel are needed to match the performance of the unaided human eye.

Is symbolic information also important? Spoken words and text are the primary means of communication between humans. As machine systems become more intelligent, speech and written text will grow in importance for human-machine communication as well.

Relationships between maps, images, and words are critical. To be useful, points and regions on a map must be characterized and labeled. Attributes (such as range, texture, color, shape, size, and motion) in visual images need to be measured, and objects need to be recognized (i.e., identified).

3. SITUATION ASSESSMENT

The types of situations that are important for future NATO missions scenarios involve urban, rural, wooded, and mountainous terrains and the sky above them. The type of entities that are important are friendly and enemy forces, buildings, roads, bridges, trees, vehicles, humans, and

animals. The entity attributes and relationships between entities that matter are their position, movement, state, and size -- and in the case of intelligent entities -- their capabilities and intentions.

3.1 The Problem of Complexity

The world is infinitely rich with detail. The mission environment contains a practically infinite variety of real objects, such as the ground, rocks, grass, sand, mud, trees, bushes, buildings, posts, ravines, rivers, roads, enemy and friendly positions, vehicles, weapons, and personnel. The environment also contains elements of nature, such as wind, rain, snow, sunlight, and darkness. All of these objects and elements have states, and may cause, or be part of, events and situations. The environment contains a practically infinite regression of detail, and the world itself extends indefinitely far in every direction.

Yet, the computational resources available to any intelligent system are finite. No matter how fast and powerful computers become, the amount of computational resources that can be embedded in any practical system will be limited. Therefore, it is imperative that the intelligent system focus the available computing resources on what is important, and ignore what is irrelevant.

3.2 Focus of Attention

Fortunately, at any point in time and space, most of the detail in the environment is irrelevant to the immediate task of the intelligent system. Therefore, the key to building practical intelligent systems lies in understanding how to focus the available computing resources on what is important, and ignore what is irrelevant. The problem of distinguishing what is important from what is irrelevant must be addressed from two perspectives: top down and bottom up.

In top down, behavioral goals define what is important. The intelligent system is driven by high level goals and priorities to focus attention on objects specified by the task, using resources identified by task knowledge as necessary for successfully accomplishing given goals. Top down goals and high level perceptions generate expectations of what objects and event might be encountered during the evolution of the task and which are important to achieving the goal.

In bottom up, the important aspects include the unexpected, unexplained, unusual, or dangerous. At each level of the sensory processing hierarchy, processing functions detect errors between what is expected and what is observed.

3.3 System Complexity

Intelligent systems are inherently complex. In order to be intelligent, systems must have a rich and detailed model of the world that is kept up to date by a sensory processing system that collects information from a large number and wide variety of sensors. An intelligent system must be able to reason about the past and plan for the future over a time horizon that extends many hours, or even days and weeks into the future.

Hierarchical layering is a common method for organizing complex systems that has been used in many different types of organizations throughout history for effectiveness and efficiency of command and control. In a hierarchical control system, higher level nodes have broader scope and longer time horizons with less concern for detail. Lower level nodes have narrower scope and shorter time horizons with more focus on detail. At no level should a node have to cope with both broad scope and high level of detail. This enables the design of systems of arbitrary complexity, without computational overload in any node and any level.

For example, at the top of the military command and control hierarchy, strategic objectives and priorities influence the selection of goals and the prioritization of tasks throughout the entire hierarchy. However, the details of execution are left to subordinates.

At intermediate levels, tasks with goals and priorities are received from the level above, and sub tasks with sub goals and attention priorities are output to the level below. In the intelligent vehicle environment, intermediate level tasks might be of the form <go to position at map coordinates x,y>, <advance in formation along line z>, <engage enemy units at time t>, etc. The details of execution are left to subordinates.

At each level in the task decomposition hierarchy, higher level more global tasks are decomposed and focused into concurrent strings of more narrow and finer resolution tasks. The effect of each hierarchical level is thus to geometrically refine the detail of the task and limit the view of the world, so as to keep computational loads within limits that can be handled by individual agents, such as intelligent computational nodes, or human beings.

4. TECHNOLOGY READINESS

For the most part, the individual technologies necessary for intelligent semi-autonomous vehicle systems are available. To the extent that the individual technologies have shortcomings, it is because they are not integrated into a system architecture that enables them to draw information from other technologies. For example, image processing

systems have problems in analyzing and understanding scenes largely because they are not integrated with inertial sensors, or provided with knowledge of lighting conditions, or with range data from radar, stereo cameras, or laser range imaging devices, nor do they use information from topographical maps or navigational instruments. In most cases, use of all of this additional information would remove the ambiguity from image analysis, and vastly improve the performance of image processing systems.

A great deal is known about sensing, filtering, recursive estimation, image analysis, uncertainty, knowledge representation, system identification, game theory, optimization, reasoning, planning, prediction, simulation, and control. The most important technology that is missing, or needs improving, is a system architecture that provides for the integration of data from sensors with other sources of knowledge into a dynamic world model with a value judgment system, and supports intelligent behavior generation at a multiplicity of levels of range and resolution in space and time. Specifically, what is required is a system theory and reference model architecture that integrates and coordinates:
1) planning for the future with many different time horizons, each with a different level of range and resolution;
2) reasoning about discrete events, objects, and symbols with many different levels of abstraction;
3) representation of information about the world in maps, images, lists, and frames with many different levels of range, resolution, and abstraction;
4) closing of reactive dynamic control loops with continuous feedback at many different sampling rates and bandwidths; and
5) focusing of attention and computational resources on what is important, ignoring what is unimportant, at all levels.

4.1 A System Architecture

4-D/RCS provides a theoretical framework and reference model architecture that meets the requirements stated above. The NIST (National Institute of Standards and Technology) RCS (Real-time Control System)[1,2] with the German (Universitat der Bundeswehr Munchen) VaMoRs 4-D approach to dynamic machine vision [3,4]. It incorporates a Laser Range Imager (LADAR) camera build by Dornier, a computer-aided mission planning, and terrain visualization technology developed by the U.S. Army Research Laboratory. 4-D/RCS is designed to provide the U.S. DoD Demo III unmanned ground vehicle project with an open system operational architecture that will facilitate the integration of a wide variety of subsystems, such as a foveal/peripheral CCD color camera pair, a LADAR, an inertial guidance package, a GPS satellite navigation system, stereo image processing algorithms developed at the NASA Jet Propulsion Lab, and a HMMWV telerobotic driving system with interfaces for a wide variety of mission packages.

The intended scope of the 4-D/RCS architecture is the design, development, integration, and testing of intelligent supervised autonomy controllers for experimental military vehicle systems. 4-D/RCS provides mechanisms by which intelligent vehicle controllers can analyze the past, perceive the present, and plan for the future. It enables systems to assess cost, risk, and benefit of past events and future plans, and to make intelligent choices between alternative courses of action. A single node in the 4-D/RCS architecture is illustrated in Figure 1.

An example of a 4-D/RCS reference model architecture for a semi-autonomous unmanned ground vehicle is shown in Figure 2. Task Decomposition (TD) modules in nodes at the upper levels in the hierarchy make long-range strategic plans consisting of major milestones, while lower level Task Decomposition modules successively decompose the long-range plans into short-range tactical plans with detailed activity goals. Sensory Processing (SP) modules at lower levels process data over local neighborhoods and short-time intervals, while at higher levels, they integrate data over long time intervals and large spatial regions. At low levels, the knowledge database in the World Model (WM) is short term and fine grained, while at higher levels it is broad in scope and generalized. At every level, feedback loops are closed to provide reactive behavior, with high-bandwidth fast-response loops at lower levels, and slower more deliberative reactions at higher levels.

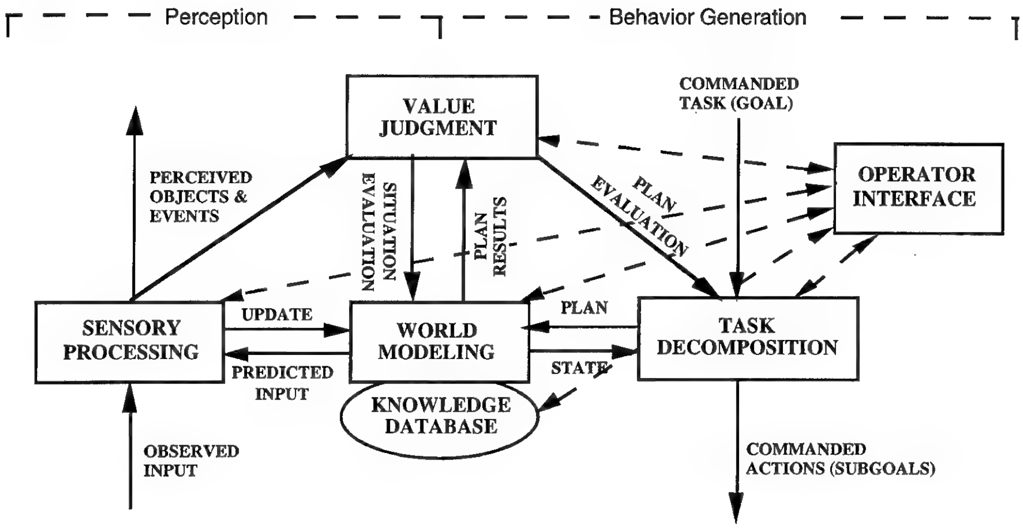

Figure 1. A node in the 4-D/RCS reference model architecture. The functional elements of an intelligent system are task decomposition (planning and control), sensory processing (filtering, detection, recognition, and interpretation), world modeling (store and retrieve knowledge and predict future states), and value judgment (compute cost, benefit, importance, and uncertainty). These are supported by a knowledge database, and a communication system that interconnects the functional modules and the knowledge database. This collection of modules and their interconnections make up a generic node in the 4-D/RCS reference model architecture. Each module in the node may have an operator interface.

At each level, state variables, entities, events, and maps are maintained to the resolution in space and time that is appropriate to that level. At each successively lower level in the hierarchy, as detail is geometrically increased, the range of computation is geometrically decreased. Also, as temporal resolution is increased, the span of interest decreases. This produces a ratio that remains relatively constant throughout the hierarchy. As a result, at each level, task decomposition functions make plans of roughly the same number of steps. Sensory processing functions compute entities that contain roughly the same number of sub entities. At higher levels, plans, perceived entities, and world modeling simulations are more complex, but there is more time available between replanning intervals for planning processes to search for an acceptable or optimal plan. Thus, hierarchical layering keeps the amount of computing resources needed in each node within manageable limits.

Hierarchical layering in the 4-D/RCS provides mechanisms for focusing the computational resources of the lower levels on particular regions of time and space. Higher level nodes with broad perspective and long planning horizon determine what is important, while the lower levels detect anomalies and attend to details of correcting errors and following plans. In each node at each level, computing resources are focused on issues relevant to the decisions that must be made within the scope of control and time horizon of that node.

The 4-D/RCS hierarchy also supports focusing of attention through masking, windowing, and filtering based on object and feature hypotheses and task goals, as well as by pointing high resolution regions of sensors at objects-of-attention. At each level, masks and windows are used to focus computational resources on objects and events that are important to the mission goal.

At each level along the time line from the present (t = 0), short-term memory is much more detailed than long-term memory, and plans for the immediate future are much more detailed than plans for the long term.

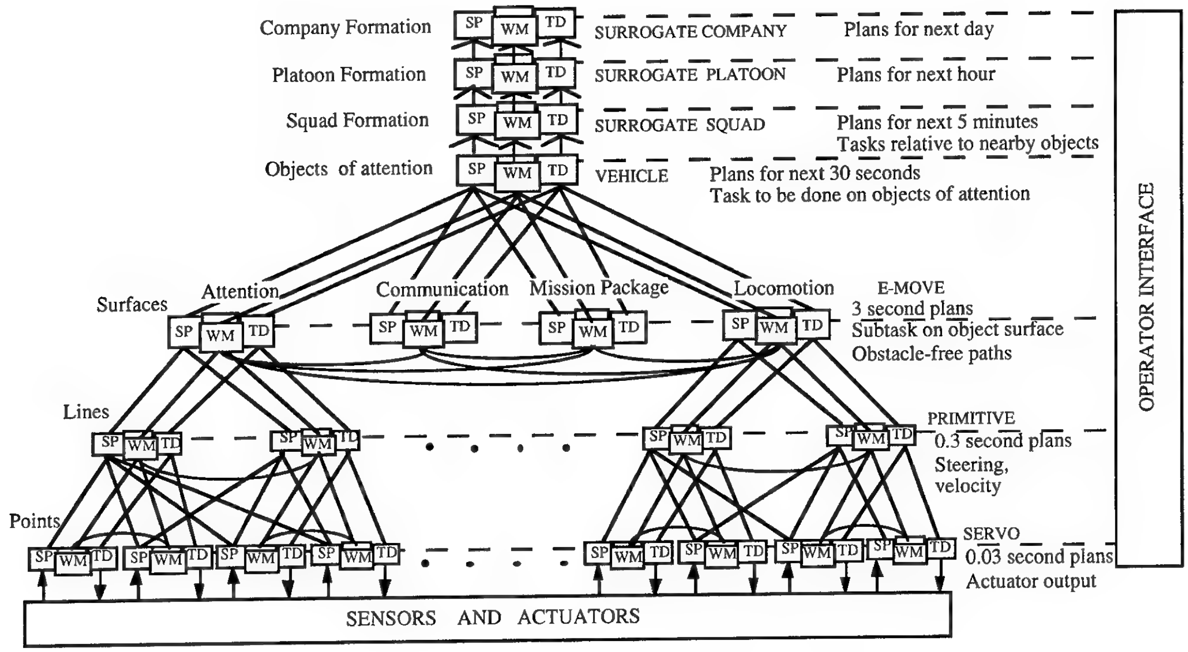

Figure 2. A 4-D/RCS reference model architecture for an individual vehicle. Processing nodes are organized such that the task decomposition (TD) modules form a command tree. Information in the knowledge database (KD) is shared between world modeling (WM) modules in nodes within the same subtree. KD modules are not shown in this figure. On the right, are examples of the functional characteristics of the task decomposition (TD) modules at each level. On the left, are examples of the type of entities recognized by the sensory processing (SP) modules and stored by the WM in the KD knowledge database at each level. Sensory data paths flowing up the hierarchy typically form a graph, not a tree. Value judgment (VJ) modules are hidden behind WM modules. A control loop may be closed at every node. An operator interface may provide input to, and output from, modules in every node.

At each level in the sensory processing hierarchy, lower level entities are grouped into higher level entities. The effect is to encapsulate the detail of entities and events observed in the world in higher level entities and events with broader scope but reduced resolution. This tends to keep the computational load of processing sensory data within manageable limits at all levels of the hierarchy.

4.2 Levels of Abstraction

The 4-D/RCS model addresses the problem of intelligent control at three levels of abstraction: 1) a conceptual framework, 2) a reference model architecture, and 3) an engineering guideline.

1. A Conceptual Framework

At the highest level of abstraction, 4-D/RCS is intended to provide a conceptual framework for addressing the general problem of intelligent vehicle systems operating in man-made and natural environments to accomplish mission goals supervised by human commanders.

The 4-D/RCS conceptual framework spans the entire range of operations that affect intelligent vehicles, from those that take place over time periods of milliseconds and distances of centimeters to those that take place over time periods of months and distances of many kilometers. The 4-D/RCS model is intended to allow for the representation of activities that range from detailed dynamic analysis of a single actuator in a single vehicle subsystem to the combined activity of planning and control for hundreds of vehicles and human beings in full dimensional operations covering an entire theater of battle. The 4-D/RCS architecture is also designed to integrate easily into the information intensive structure of Force XXI Operations and advanced concepts for the strategic Army and Marine Corps of the early 21st century.

In order to span this wide range of activities within a single conceptual framework, 4-D/RCS adopts a multilevel hierarchical architecture, with different range and resolution in time and space at each level.

2. A Reference Model Architecture
At a lower level of abstraction, 4-D/RCS is intended to provide a reference model architecture for supporting the design and development of intelligent vehicle systems and to provide a theoretical basis for the development of future standards. In order to accomplish this, the 4-D/RCS architecture follows as closely as possible the existing command and control structure of the military hierarchy in assigning duties and responsibilities and in requiring knowledge, skills, and abilities.

4-D/RCS defines functional modules at each level such that each module embodies a set of responsibilities and priorities that are typical of operational units in a military organization. This enables the 4-D/RCS architecture to map directly onto the military command and control organization to which the intelligent vehicles are assigned. The result is a system architecture that is understandable and intuitive for human users and integrates easily into battle space visualization and simulation systems.

3. Engineering Guidelines
At a still lower level of abstraction, 4-D/RCS is intended to provide engineering guidelines for building and testing, and eventually using, specific instances of intelligent vehicle systems. In order to build a practical system in the near term, 4-D/RCS engineering guidelines will be developed bottom-up, starting with a single vehicle and its subsystems. The 4-D/RCS engineering guidelines define how intelligent vehicles should be configured in order to work together in groups with other intelligent vehicles, both manned and unmanned, in units of various sizes.

The type of problems to be addressed by the 4-D/RCS engineering guidelines include the following:
1) navigation and driving both on and off roads,
2) responding to human supervisor commands and requests,
3) accomplishing mission goals and priorities amid the uncertainties of the battlefield,
4) cooperating with friendly agents,
5) acting appropriately with respect to unfriendly agents, and
6) reacting quickly, effectively, and resourcefully to obstacles and unexpected events.

Intelligent vehicle systems will consist of a variety of sensors, actuators, navigation and driving systems, communications systems, mission package interfaces, and weapons systems controlled by an intelligent controller.

The intelligent vehicle must be able to communicate easily and naturally with human operators and be integrated into the military command and control structure in a manner that is natural and intuitive to military personnel. Specifically, the system should be able to take commands, to ask or offer advice, to report what is important, and to respond to queries.

5. SUMMARY AND CONCLUSIONS

The technology requirements to implement improved situation awareness have been specified. The principal impediment to machine perception is seen to lie in a lack of system architecture that integrates the currently available technologies in signal processing, scene analysis, image understanding, knowledge representation, value judgment, and behavior generation. A theoretical framework and reference model architecture for semiautonomous intelligent unmanned ground vehicles has been discussed. It is suggested that implementation of this architecture will result in an intelligent vehicles system with a level of performance that would be useful to field commanders in tactical situations.

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Unmanned Tactical Aircraft: A Radically New Tactical Air Vehicle and Mission Concept

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SUMMARY

The Unmanned Tactical Aircraft (UTA) is a complete airpower system which enables a general purpose high performance aircraft to perform a full range of lethal missions without the physical presence of a pilot in the aircraft. The system allows the pilot to be *virtually present*, so that his moral and tactical judgment are retained without exposing him to capture or casualty. Without the pilot, the air vehicle will be optimized for a combination of performance and affordability and can be much less complex and expensive than a comparable manned vehicle. UTAs will be effective in a variety of missions in conflict situations but need not be flown in peacetime beyond minimum maintenance needs; training and mission rehearsal will be done using simulations with the actual virtual pilot interface in the loop. This concept will enable unprecedented affordability in the system. Current estimates are up to 40% reduction in acquisition cost and 50% reduction in operations and support cost. A mix of manned aircraft and UTAs, both exploiting the emerging information architecture for targeting and control provides a distinct new option for national air forces which may be unable to afford a "full" force structure of manned aircraft in the constrained budget environments of the future.

1.0 UTA CONCEPT OVERVIEW

The UTA concept encompasses a broad class of recoverable air vehicles designed to conduct the full range of tactical missions using ordinary aircraft weapons, onboard sensors, and tactics. UTAs will exploit the many sources of offboard information available in the modern theater of operations. Flexible offboard control of the air vehicle places the operator at the center of the emerging information architecture whether the control station is ground, air, or sea-based. This will enable the operator to exploit information from on-board sensors, off-board reconnaissance and surveillance sensors, and theater databases of information from all sources.

UTAs will capture the benefits of both manned and unmanned operations. As an unmanned system it can be fearless, performing missions which are too hazardous for pilots, and can be expended as required by the situation and the value of the tactical objectives. It can operate without regard for the physiological limitations of the human pilot -- sustained maneuvers about all axes, extremely long duration operations, and hazardous environments, including chemical, biological, and nuclear environments. As a manned system it will fully use the rational, judgmental, and moral qualities of the human operator and provide flexible operational capabilities needed to operate in a variety of situations, including operations with complex rules of engagement in the presence of various noncombatant parties. This is the only concept which captures these benefits in a single system.

The key to UTA is to "keep the operator's head in the cockpit while leaving the rest of him at home". UTA will be uninhabited, but otherwise will function as a piloted vehicle, enabling the operator to use the full range of his capabilities to solve tactical problems. This is the key which will allow UTAs to operate as flexibly and effectively as manned aircraft. UTAs will operate from ordinary airfields and fly in controlled national airspace. They will conduct missions in peacetime, in crisis situations and in wartime. UTA operators will observe rules of engagement and make the critical decisions to use or refrain from using force, and operate in uncertain and confusion situations with poor planning. *These characteristics distinguish UTA from other unmanned systems like cruise missiles and UAVs (Unmanned Air Vehicles).*

1.1 Integrated System Concept

A schematic of the concept for an integrated UTA system is shown in Figure 1. The schematic shows the basic concept of the system. The operator interfaces with the flight system using a pilot mission interface. This integrates onboard information -- avionics and onboard sensor data -- with offboard information -- planning, support, and intelligence, surveillance, and reconnaissance data -- to perform mission functions. This view of the system shows the core issues which must be addressed to make an integrated UTA system a reality, including:

- onboard sensor control and multisensor data fusion;
- avionics systems;
- secure data links from aircraft to operator interface;
- pilot mission interface integration;
- displays and human factors;
- offboard data integration;
- information processing and fusion;
- mission planning and control.

1.2 Concept Of Operations

One view of the concept of operations for UTA is presented in Figure 2. UTA airframes could be land-based or sea-based, and could be a conventional takeoff and landing aircraft or have vertical takeoff and/or landing modes. This will be shaped by the roles and missions selected for the air vehicles when they are designed. Command and control of the UTA force will be accomplished using line-of-sight and satellite

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communications data links. Airborne relay can be used to extend the range of line-of-sight links as for any other aircraft communications system. Future radios will allow airborne networks to be formed among tactical aircraft - UTAs and piloted aircraft - in the local area of operations. This will facilitate data sharing and extend the effective range of line-of-sight data links, particularly in areas with difficult terrain masking.

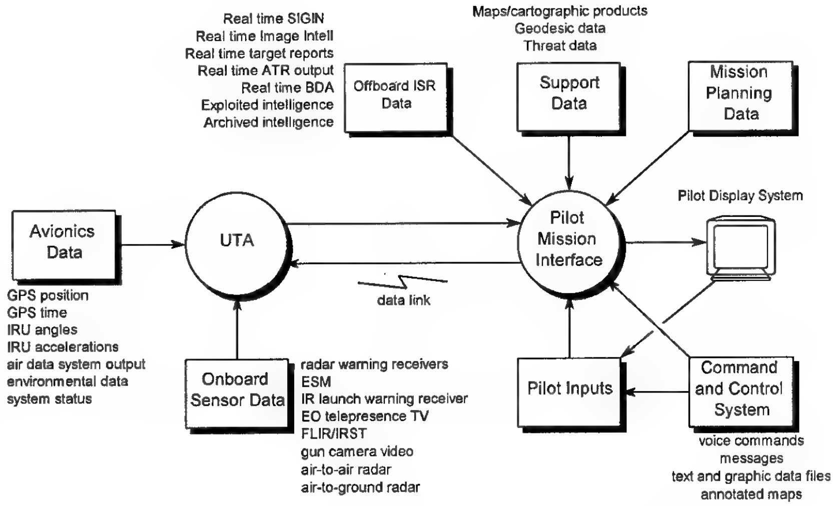

Figure 1. Schematic of UTA Concept

The pilot's control station could be land-based, ship-based, or integrated into an airborne command and control aircraft. In the longer term it may also be possible to integrate it into the cockpit of other tactical aircraft. The airborne control option offers the maximum flexibility, but will pose the greatest miniaturization and integration challenges. The initial demonstrations of the control station will most likely be done using a ground station, which can make maximum use of commercial equipment and prototype hardware and software during the development phase. The shipboard control option is midway between ground and air basing in terms of system integration and equipment miniaturization, but offers significant system integration challenges of its own, particularly in the areas of communications.

The key to UTA's flexible capabilities will be the achievement of *variable autonomy* in the system as a whole. This refers to managing system functionality to allow the pilot to control any or all system functions depending on the tactical situation and operator's judgment, while making maximum use of system autonomy to control all other functions. The air vehicle will be capable of complete autonomy for all functions except authorization of the use of lethal force (weapons release), and will normally operate in a nearly autonomous way. The pilot assisted by systems within the control station will be capable of direct control of nearly all onboard functions, but normally will control only a few functions directly and will serve as a mission objectives controller. The system (onboard and offboard systems) will be capable of adapting to changes in the pilot's preferences for control and in the situation (for example, failure modes and communications outages) to vary the degree of autonomy to best suit circumstances. In this way the creativity, skill and moral judgment of the pilot and the autonomous capabilities of the computer-controlled system can be *complementary*, and not substitutes for each other. This is the core enabling technology area for UTA and achieving it will be the fundamental challenge in realizing the full promise of the system.

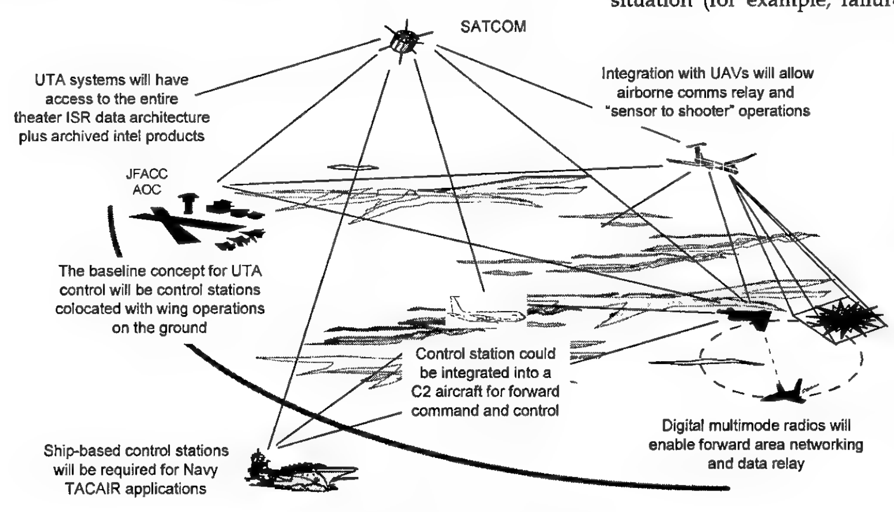

Figure 2. UTA Concept of Operation

UTA systems are envisioned as operating much like a piloted aircraft during wartime, but they will operate very differently at other times. Piloted aircraft must be operated regularly in peacetime to maintain aircrew proficiency, exercise

avionics and weapon systems, and keep the aircraft in flying condition. A 15-year lifetime with 30 hours of training per month results in a 5400 flight hour lifetime; adding wartime hours yields design lifetimes in the 7000 hour range. This has a fundamental impact on the way the piloted aircraft is designed and maintained, and therefore on how it accrues cost.

UTA will fly very infrequently in peacetime. Its characteristics will be more like a "wooden round" weapon or cruise missile than a tactical aircraft. Since the pilot operates the UTA through a remote interface, it doesn't really matter whether the aircraft is flying for the pilot to receive his tactical training. Flight skills such as takeoffs and landings, refueling, formation flying, and tactical maneuvering are not significant since they will be mainly accomplished autonomously by onboard systems, guided by pilot input on mission objectives. All this training can be accomplished using interactive simulations of the battlefield and the real pilot interface equipment -- training as the operator will fight. Reducing design lifetime flight hours by a factor of 3-5 will fundamentally affect UTA design requirements and cost relationships.

UTA as a "wooden round" system will operate and be supported differently than manned aircraft. Only a few UTA will be fully operational at a given time. This will necessitate only a cadre of maintainers and supporters to be active and incurring cost in peacetime. The active units will rotate through the stored force over time, evening out the flight hours and keeping the force as a whole in readiness. A full complement of pilots will be needed, but other manpower requirements will be greatly reduced. This is allowed by the simple fact that a large air force usually is not needed in peacetime Manned aircraft can do most peacetime jobs (since they must be kept active), supplemented by the smaller number of active UTA.

In time of war the UTAs would be surged to fill out the full force of tactical aircraft. The pilots would be fully trained and ready to operate exactly as they trained. Additional maintainers and supporters would be surged, perhaps from reserves to match the UTA activation schedule. The concept for achieving effective and timely surge activation would obviously be among the challenges in developing UTA into a full operational system.

1.3 Emergence of the UTA Concept

There has been a perceived if latent need for a system like UTA for many years. This is partly responsible for the many variations on man-in-the-loop standoff weapons and sensor-carrying UAVs that have been fielded over the past two decades. Of these, many of the air-to-ground weapons have been successful, but attempts to achieve really flexible multimission operations in an unmanned system have been disappointing until quite recently.

UTA as a viable system concept emerges from the confluence of technology trends in the hitherto separate areas of manned and unmanned air vehicles, supported by the explosion in information and communications technologies.

UAVs have only begun to receive public notoriety in recent years. Examples include the Israeli operations against Syria, the utilization of the several short range systems during Desert Storm, and Predator operations in Bosnia. The latest generation of U.S. UAVs - the Tier II+ Global Hawk and Tier III-Dark Star HAE (High Altitude Endurance) systems - will fully embody the advances proven in these systems and advance far beyond them in system capabilities. Although these are advanced aerodynamic vehicles with highly capable sensor systems, the major advances in their capabilities will be in the area of command and control, including NRT (near real-time) control by manned operators. HAE operators will be give intimate knowledge of the vehicle and all its systems and will be able to completely control all mission parameters in real time. They will be supported by advanced situation displays and mission planning tools capable of adapting complete missions to changing tasks and tactical situations on time scales of minutes. Advanced concepts for integrating strike and ISR (Intelligence, Surveillance and Reconnaissance) operations envision synchronizing manned strike aircraft and HAE missions by integrating these man-in-the-loop remote control capabilities with strike command and control in real time.

As UAVs have evolved into flexible systems with fast-paced operator involvement, manned aircraft have become more autonomous. This began with "fly-by-wire" flight control in the 1970s and has progressed with automated flight control, navigation and guidance, and propulsion control to the point that pilots of modern tactical aircraft are literally unable to fly and fight their aircraft without the proper functioning of these systems. In parallel, cockpit technologies have automated the functions of sensor and weapon management, information processing, and situational awareness display so thoroughly that pilots depend more on what their systems tell them than the traditional "out of the cockpit" view and "seat of the pants" cues. Most warfare missions cannot be performed at all when cockpit systems are less than fully functional. In a real sense, modern tactical pilots are high level mission controllers, relying on automated systems to do the real work of performing the mission on a systems level.

The UTA concept is the logical extrapolation of these converging sets of technologies. If the tactical information normally found in the cockpit can be communicated in real time to remote controllers and if the high level information fusion, situational awareness display, planning and mission control functions of the controller station can be compressed from UAV to tactical aircraft timelines, the need for an inhabited cockpit no longer exists. What is lost is the pilot's sense of onboard awareness; this will detract from some missions. What is gained is access to the emerging theater information environment, powerful processing tools, and freedom from physiological constraint; these will enhance other missions. The ultimate application of UTA technology will depend on the balance between these two factors. In any event, UTA is a next logical step in tactical airpower.

2.0 MILITARY IMPLICATIONS

With the current choices in air vehicle systems, there are limited degrees of freedom in fielding and operating tactical air forces under budgetary and mission constraints. UTA offers a system alternative which has fundamentally different characteristics - a new degree of freedom for force planners. UTA could have dominant performance in some missions and might be quite limited in others. Perhaps most importantly it

can offer a reduced cost option to supplement or complement piloted aircraft. These characteristics suggest that UTA can enter the force mix of many national air forces if the development of the technology bears out the promise of the concept.

2.1 Dominant Performance

The UTA vision in the long term is a new class of air vehicles whose design and performance will be tailored to enhance mission effectiveness, not to meet the physiological needs of the aircrew.

The new class of UTA vehicles has the potential to achieve dominant performance over manned vehicles used for the same general kinds of missions. Freed from man's physiological constraints, a designed from scratch UTA can achieve much higher performance than a manned vehicle. New design concepts can be used in the areas of structural design, aircraft layout, propulsion system design, and use of non-man rated systems, resulting in substantial performance increases above the 10-15% weight savings directly due to eliminating the cockpit and aircrew. Designers will be able to provide super-maneuverability (20+ sustained g's, high acceleration about all axes), longer endurance (beyond man's limit), higher speed, and/or higher altitude tailored for mission effectiveness, not just to meet the limits of the aircrew.

UTA designs will also have advantages for signatures. Manned aircraft require a cockpit located high and forward on the fuselage. This largely dictates the layout of the remainder of the aircraft. UTA can be laid out specifically to address difficult signature problems like inlets and exhausts, wing-body intersections, and antenna and optical aperture locations. Innovative layouts can be used - for example, locating more observable systems like landing gear doors and access doors and drains on the "top" and designing the "bottom" to be fair - since there is no up or down orientation to a vehicle without a pilot. Different materials can be used for signatures design, since UTA will fly different mission profiles and have a shorter design lifetime than manned aircraft.

2.2 Expanded Military Options

The UTA vision is of a weapon system which expands tactical aircraft mission options by eliminating the risk of casualty or capture of aircrews and performing new kinds of missions more effectively than conventional piloted aircraft.

The advantages of unmanned strike operations are apparent. UTA can perform tactical air missions without exposing aircrews to risk of capture or loss. This is a particularly valuable attribute for operations other than war, politically sensitive operations, and operations which have high value but which are inherently too dangerous for manned aircrews to perform. Aircrews of all the alliance nations have shown their willingness to accept the risks inherent in these kinds of operations, and have done well when required to perform them. However, the balance of acceptable risk is changing in the post-Cold War world. Public opinion throughout the West is increasingly intolerant of losses in operations which (in contrast to Cold War missions) are perceived by some as being less clearly in the national interest. This enhances the potential value of systems like UTA which can directly eliminate this category of risk.

In some cases the hazardous missions can be done by cruise missiles, and this will continue to be a good solution for the foreseeable future. However, many missions of this kind must be undertaken under conditions of uncertainty, poor planning data, and complex (perhaps politically sensitive) rules of engagement. These factors nearly always make manned strike the preferred option. UTA will be capable of combining the advantages of manned and unmanned operation, so it will offer a fundamentally new way to approach this class of missions.

Finally, UTA can enable missions to be performed in an entirely new ways, capitalizing on the explosive growth of theater information systems for real time ISR, situation awareness, and targeting. Fusing information from many sources will allow UTA pilots to compensate for the reduced situation awareness inherent in remote operation. It will allow these data to be used without the need to send large amounts of digital image data to cockpits of manned aircraft. This is an important element in making UTA feasible and effective.

One example of new mission concepts is the idea of *loiter weapons* for quick reaction strikes in all warfare scenarios. UTAs with conventional air-to-ground weapons can loiter outside the immediate area of operations indefinitely - far beyond the capabilities of pilots - using air-to-air refueling to extend the mission. This would allow very quick reaction "call for fire" strikes in situations where the full complement of ground and air-based weapons are not available to engaged troops. Light forces engaged in peacekeeping would be a good example of this. Loiter weapons could also be used to enforce deterrence operations. In any event this concept of mission operations is not available with manned aircraft except at great cost.

2.3 Mission Effectiveness

The UTA vision is of an unmanned or virtually manned system which is capable of the full range of piloted aircraft missions and operations.

This is a goal which seems to be largely attainable based on the rapid and continuing growth of the technologies which support UTA. However, it is unreasonable to believe that all missions can be done equally well or can be done at all in the same generation of vehicles. UTA capability will grow as the technology develops and as user communities learn how best to use systems of this kind.

The class of UTA vehicles extends from more flexible and capable versions of currently deployed surveillance and UAVs to future full spectrum unmanned aircraft. Missions for UTA's in order of increasing complexity are as following:

- ISR and Battle Damage Assessment (BDA);
- Electronic Warfare (EW);
- Suppression of Enemy Air Defense (SEAD);
- Fixed Target Strike;
- Theater Ballistic Missile and Cruise Missile Defense ;
- Air Defense;
- Interdiction and Mobile Target Strike;
- Close Air Support;

- Air-to-Air Combat.

This list encompasses the core tactical aircraft mission set. Other missions will also be possible, such as unmanned airlift and special mission aircraft. The concept extends to non-aircraft applications, such as reduced or unmanned sealift and new ways to approach UGVs (Unmanned Ground Vehicles). In this paper the focus is on tactical aircraft missions.

ISR and EW support missions will be feasible in the very near-term. Unmanned ISR is currently being done today with UAVs. EW could be done with these airframes or with modified conventional tactical aircraft. For these missions the UTA concept would apply to improving the currently limited operator interfaces to expand the mission envelope and allow these missions to be performed more dynamically and in a greater variety of operating environments. For example, this could enable the "Photointerpreter in the loop" concept for real-time targeting and BDA.

SEAD and fixed target strike missions are also possible in the near-term, though the full potential will not be reached until the technology is fully mature. These missions are a short step for UTA, since the technologies needed to employ these sensor and weapon systems is essentially available today. For example, the most advanced strike aircraft today (F-117 with upgraded avionics is a good example) are so automated that the pilot is required to do little beyond authorizing weapon release; the full capabilities of the pilot are not really used in this class of missions. The major UTA technology challenge will be to develop and demonstrate the methods to operate an unmanned aircraft like a piloted aircraft, using air traffic control procedures, operating from ordinary airfields, and so on. These are likely to be the first combat missions for which new UTAs are acquired.

SEAD is particularly appealing for UTA because it is a "dirty and dangerous" mission that pilots do not like to fly, but which is essential in combat air operations ranging from peacekeeping to full integrated theater warfare. Thus unmanned SEAD has the advantage of minimizing the inevitable resistance of pilots to expanding unmanned strike systems at the expense of manned platforms.

The interdiction mission will be more difficult since the UTA must search for and find its target based on cross cues from other theater assets or information from its own sensors. In either case the onboard system must eventually acquire the target and transmit data back to the operator so he can choose aimpoints and responsibly give consent for weapons release. All this must be done in a very short time, which will stress communications and data processing systems. Human factors in the operator interface will be important to reliable performance by the remote pilot. Extrapolating sensor, information processing, and communications technology this does not appear to be an insuperable obstacle in the medium term (10-15 years); however, the system must be integrated and tested before its reliability and effectiveness can be assured.

The Air-to-Air Combat will probably be the most difficult mission for UTA because it is so dynamic and depends so heavily on pilot skill and situational awareness. BVR (Beyond Visual Range) combat would seem to be quite compatible with the UTA concept, but this cannot always be assured. The applicability of UTA technology to close-in "furball" combat is in question. Much of what is done in this situation is based on the pilot and his ability to monitor his sensors and visually acquire the attacking aircraft. This is always required when visual firing rules of engagement are in force. The UTA must remotely emulate the pilot's visual cues based on imaging and other situational awareness sensors on the aircraft which downlink the data in real time to the control station. This requires a tremendous amount of bandwidth and must be done in real time. There will be communications problems in "n-on-m" furballs with close proximity of the aircraft and highly dynamic geometry. Balanced against this is the possibility that the UTA will have a large maneuvering advantage over the adversary aircraft, and may be a match for his missiles in some situations. This will simplify the mission, but not quite relieve the need for the highest level of information exchange and the most severe demands on the situational awareness of the remote pilot. This mission will probably be the farthest term application for UTA; ultimately its feasibility is yet to be established by our current understanding of the technologies involved.

2.2 Tactical Deterrence

One of the primary advantages of the UTA system is the elimination of risk of pilot loss in high threat areas. Today's pilots are facing evolving and poorly understood threats as NATO forces are becoming more and more involved in a world populated by aggressive regional adversaries armed with the best of both former Soviet and Western technology. Western involvement is increasingly in operations in which the proactive combined arms doctrines of warfare demonstrated fully in Desert Storm cannot necessarily be used. These missions include peacemaking, situation monitoring, crisis management, and limited intervention, particularly for precision strike.

Public opinion does not support Western military operations with a high risk of casualties and places rigorous demands for limited collateral damage and casualties to civilian populations. Thus, strike operations are increasing taking place with restrictive and complex rules of engagement. The UTA can provide a radically new kind of tactical aircraft to allow aggressive operations without exposing air crews in politically sensitive operations.

Under these conditions deterrence of conflict is greatly preferred to active operations. Unmanned strike opens up possibilities for new concepts of tactical deterrence. Currently, the perceived political and military costs of actions against potential adversaries using manned tactical airpower can be high enough to deter us from performing them. We lack ways of deterring hostile action against our forces at the same time we are exposing our aircrews and search and rescue teams to risk of loss or capture under restrictive rules of engagement and constrained concepts of operation.

In operations in places like the Balkans, we are able to use our airpower only due to the bravery and skill of our aircrews - and we have suffered losses. Changes in the aggressiveness of the threat (e.g. the former Yugoslav armed forces) could raise the cost beyond expectations of benefit, and we could be deterred from maintaining our operations. Variations in national policy further raise the risk that multinational forces could be deterred from action by the policies of

their most sensitive members, making allied actions much more difficult to coordinate and pursue.

UTA would allow these operations to be performed with less risk for us and more risk for the enemy, since the vehicles could be more fearless as required by the situation. They could be used to deter the enemy - if UTA is effective, they lose; if they shoot down UTA, they do not win much and they risk further UTA operations. This is the kind of asymmetry which can be used to influence adversary behavior and deter future confrontations. Much more work needs to be done to understand the potential of UTA for obtaining tactical deterrence; however, in light of the paucity of other deterrence methods, this would seem to have a high payoff.

3.0 AFFORDABILITY

The principal technical impetus for UTA is provided by the performance and unique mission opportunities it has the potential to create. However, its impact on affordability is equally distinctive and some will perceive this to be the more important factor.

Affordability has become a major driver in national defense policy as well as in individual system design. It is increasingly essential for national air forces to break out of the aircraft cost spiral. Aircraft continue to become capable but costs are also increasing, especially as fewer are produced. Because of this increased cost, fewer are produced, and these fewer aircraft must be even more capable, and so on. The affordability of the next generation of aircraft to replace the current fleet is critical because of declining defense budgets and the intractable tendency for a large portion to go towards meeting personnel, infrastructure and operating costs.

The U.S. faces the need to acquire F-22 at a projected unit cost more than $150M million, the F/A-18E/F at more than $80M and the Joint Strike Fighter with a target cost (as yet demonstrated) of $35 million or more each. Similar situations face each of the NATO nations, whether their systems are developed indigenously or not. As events play out in the uncertain future it may well be that costs of this magnitude will be unaffordable and inconsistent with the size of the force structures needed to meet individual defense needs as well as the needs of the alliance. If desired force structure targets cannot be met, or can be met only at the cost of debased quality or increased age of the fleet the national security implications for the West will be profound.

Although substantial investments are being made in "affordability technology", there is little indication of a fundamental paradigm shift in the way costs are incurred to build, own and operate tactical aircraft. Affordability gains are significant at any level, and the expectation is that further gains will be achieved at the margin by determined effort. However, other options are needed to fundamentally change cost relationships between aircraft cost and force size. Note that affordability gains in design, materials, and manufacturing technology apply equally well to UTA as to piloted aircraft.

For a given range-payload performance a UTA can be smaller and lighter than an equivalent manned aircraft. Eliminating crew systems may be worth 10-15% in weight. This may be worth an additional 5-10% weight savings when a new design is closed around it. New systems, materials and structural techniques for an airframe with reduced lifetime flight hours (e.g. designing for strength instead of fatigue life) may be worth an additional 10-15%. All-in-all a UTA may be 30-40% smaller than a piloted aircraft. Since aircraft with equivalent avionics and weapon systems are bought "by the pound", this will result in a substantial and fundamental decrease in acquisition cost. In addition to designing for enhanced performance or signatures, reduced cost can be factored into the requirements and design process, allowing a more flexible approach to designing affordability into the system.

UTA will be operated remotely, by a pilot who interfaces with the aircraft through computerized interfaces and communications links. It will be possible to train pilots realistically without flying the aircraft a corresponding number of hours per month. It will only be necessary to fly the aircraft to check functionality and keep the aircraft in current flight status on a rotating basis - not to train the aircrews. This breaks the direct connection between realistic pilot training (which is required) and actual flight operations (which incur substantial recurring cost). Separating training from flight operations will allow O&S costs for the airframe to be reduced dramatically - perhaps up to 90% for this segment of cost. Overall O&S costs may be reduced up to 50%, depending on manpower policies and mix of aircraft (manned and unmanned) in organizational elements like wings and carrier air groups.

Cost-effectiveness analyses have been conducted to determine missions and aircraft configurations which could enter future force structures. An example is shown in Figure 3. This compares UTAs using GPS munitions with advanced reduced cost cruise missiles for fixed target strike. Both systems leverage theater information systems - that is, both systems are retargetable and can efficiently use BDA information to retarget in flight. The analysis shows that a UTA which is 2-10 times *less survivable* than a manned aircraft will be cost effective if its acquisition cost is less than about $30-40M per unit. This would imply that an unmanned JSF (which would cost 40% less than a manned JSF and thus less than $30M, would be cost-effective for fixed target strike compared to the most advanced cruise missile options. Design analyses show the potential to field UTAs in the $15-20M range with performance comparable to the JSF-class of airframe. This cost-effectiveness result is typical for UTA; it will be competitive with or dominate other alternative systems in performing many kinds of tactical air missions. This result is strictly due to the reusability and long term cost advantages of the concept.

The UTA concept enables an affordability paradigm that is fundamentally different from that for conventional manned aircraft..

It will be possible for a national air force to have a large number of UTAs available for wartime operations while paying relatively little for them in peacetime - simply because they aren't used. With UTAs in the force it will be possible to maintain a large force for wartime (rich in UTAs) while operating a small force for peacetime commitments (rich in manned aircraft). The force mix of UTAs and piloted aircraft can be tailored to establish a preferred relation between surge capability for wartime and recurring costs in peacetime. This contrasts sharply with the relation for piloted vehicles, for

which recurring costs and surge capability are necessarily directly in proportion so long as pilot proficiency is maintained. This kind of solution is infeasible with piloted aircraft but can be made real with UTAs if the technology challenges can be met over the next 10-20 years.

4.0 TECHNOLOGY NEEDS

4.1 System Control

The control architecture for the UTA concept is a modular design to allow multiple control options for operational flexibility. The location of the control station (ground, air, or ship-based) and the degree of autonomy between the station and the air vehicle will be variable to facilitate a general tactical air vehicle which can be adapted to accomplish a full range of missions. Variable autonomy and allocations of tasks will allow each control station to control more than one UTA since the operator only has to focus on high level mission functions.

The functionality of the UTA control station will encompass many of the functions performed with today's tactical and reconnaissance aircraft - both manned and unmanned. This functionality can be broken out into three primary areas: 1) aircraft and mission control, including weapons delivery; 2) mission planning and navigation; 3) and intelligence and support data fusion and targeting. Basic mission control for one or more UTAs will be performed in the core control station, each of which has one pilot in the loop. The core control station is what is minimally required to operate UTA aircraft with very limited aspects of the other areas of functionality. Groups of core stations will be supported by planning, targeting and command and control stations. A view of control station functionality and modularity is shown in Figure 4. As additional UTAs are added and mission complexity increases, more stations would be added to handled the additional aircraft and influx of data. This control architecture will allow the system to be adaptable and flexible in order to meet a wide variety of mission requirements. This approach also allows the system to grow as new tactics and aircraft come into utilization.

It is envisioned that the control station have the capability to be either land, sea, or air based. These diverse locations would require the control station to be modular in design such that the "basic" control station with enough functionality to successfully easily integrated into a variety of platforms while still maintaining the enough capability to complete its mission successfully. Control of any single UTA could then be passed between different entities for optimal mission configuration.

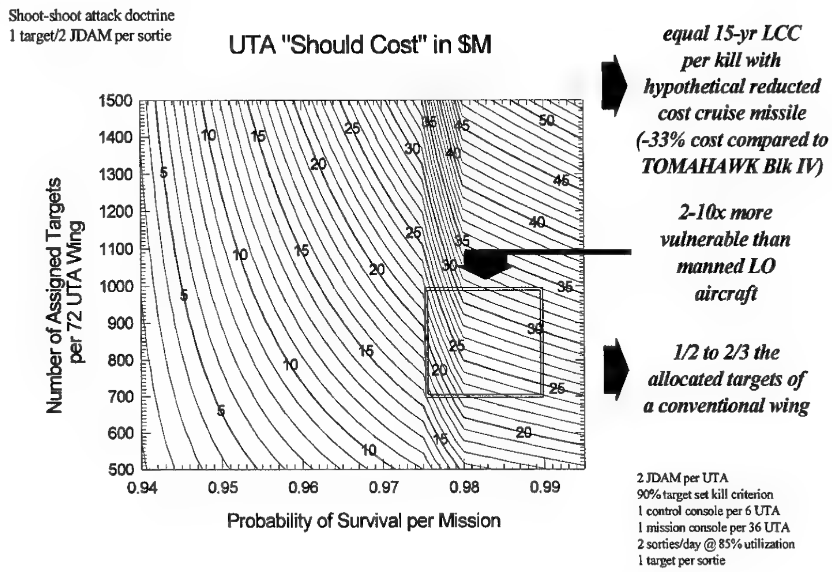

Figure 3. "Should Cost" of Cost-Effective UTA Strike Aircraft

The key concept for controlling multiple UTA's with a single control station is *variable autonomy.* The control station will have the ability to autonomously control any system or mission function in any phase of flight. The operator would allocate the control of tasks between the vehicle, control station and pilot with the ability to adapt this control based on flight conditions and changing mission requirements. The ability of the operator to off load tasking to automated systems will allow him to focus on higher level mission functions requiring human expertise such as targeting, mission sequencing, target selection, weapons release consent, retargeting, and compliance with the rules of engagement and overall flight safety.

Variable autonomy is a complex subject because a mission involves so many different functions, each of which must be controlled effectively and precisely in order to accomplish a mission. Complexity varies by phase of flight and mission. A view of UTA state transitions is shown in Figure 5. The most complex phase is combat, because weapon systems must be operated and superb situational awareness of the threat and combat arena is required. However, other phases such as ground operations will also be demanding if the unmanned system is to interoperate with manned aircraft at the same facilities.

Principal control modes for a given function in a given mission state will be direct pilot control, onboard control/command by consent, onboard control/command by negation, and onboard autonomous control. The pilot operates the system by manipulating the assignment of these control modes to controlled functions. The best pattern of assignments to functions is not currently known, nor is it known how assignments will vary among pilots in accor-

dance with their tactical judgment and piloting style. The technology for achieving variable autonomy by enabling control mode variations of this type will be a major development challenge for UTA.

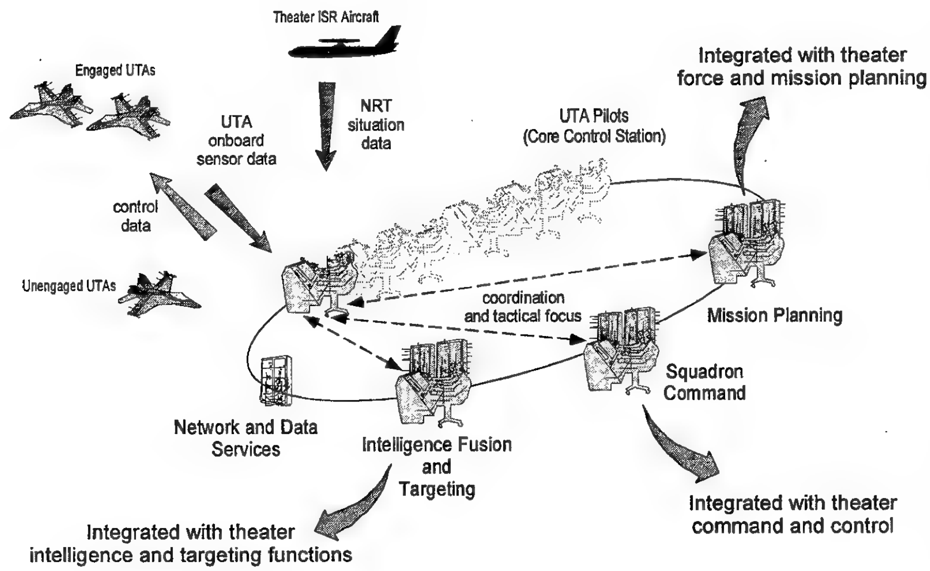

Figure 4. Control Station Configuration for a Group of UTAs

Because the UTA is lethal and will operate in cooperation with other tactical forces, the reliability of control is crucial. The system must achieve this reliability during communication link degradation and link loss. This suggests that the changing degree of control between the operator, the air vehicle and the control station is not solely the operator's decision. There are situations where the system recognizes that it can not allow high levels of operator control due to impeding conditions. In such situations, the control architecture must adjust the degree of operator and system control then notify the operator what it is done and conditions requiring this action. The conditions that create these situations and the resulting actions must be well defined within the system architecture.

There must be sufficient flexibility in the range of modes control for each function to reach to the dynamics in communications capacity, scenario conflict level, and environmental conditions. Before the mission, each operator must be able to tell the system how it intends to interact with it during the planned mission. The mission plan should include an initial event-based schedule, allocation of tasking and division of control. During mission the operator will have a full range of control modes available to react to scenario contingencies.

Current UAV ground stations were by image analysts with limited involvement from pilots. While this approach works well for UAVs performing reconnaissance missions, there are inherent limitations which must be overcome to fully exploit the UTA system. Current UAV control stations are designed to handled a very limited number of aircraft and the UAVs which it controls fly at high altitudes at fairly slow speeds. The UTA system will possibly have several hundred aircraft flying at a variety of altitudes at very high speeds carrying weapons. Because of these significant differences in operations requirements, the UTA system must employ radically new concepts for control stations. These concepts must leverage new and emerging technologies to allow the operator(s) to control/monitor the UTAs and make effective use of all the information and intelligence without being completely overloaded with all the available data. These technologies will include: Advanced high resolution displays (high dynamic range, high resolution color, wrap-around projection systems, flat workstation displays, advanced heads up displays, 3D hi-resolution displays, robust voice recognition and natural language processing, advanced databases, high speed computing, automated data fusion and correlation in real time for very large amounts of data, and the ability to selectively filter the data so as not to overload the pilot.

4.2 Communications

The communications requirements for the UTA go beyond the basic command and control. The concept requires downlinking of a variety of sensor data to the control station, interfacing the control station with intelligence assets so that real time mission planning/mission updates can be performed, BDI/BDA dissemination of intelligence gathered during the UTA mission.

The goal of the UTA system is to have a seamless communications architecture which can pass data between the aircraft and the control station through a variety of paths to ensure a robust system which operates over extended ranges. These paths include line of sight (LOS) links, SATCOM, and relay communications links. Each of these links must be compatible with the control station either on the ground or in an airborne platform such as AWACS, ABCCC, JSTARS and must be networked together for seamless connectivity. The basic idea of the communications relay link to have each of the UTA aircraft act as a communications relay for the others using an airborne network. This would allow the UTA to operate beyond line of site without having to go through satellites and also improve the robustness of the communications channel such as in high jamming environments.

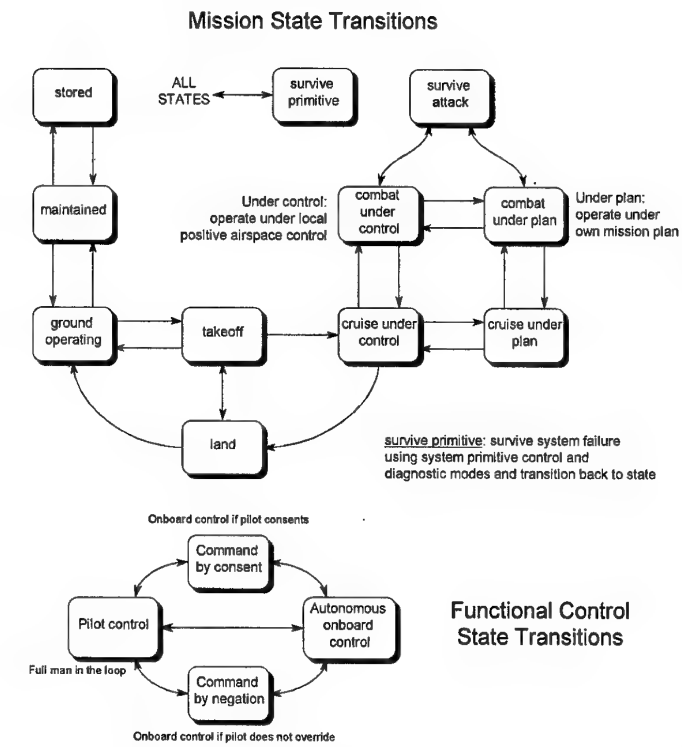

Figure 5. State Transitions and Control Modes for Variable Autonomy

In developing the communication requirements for the UTA system, a number of trades must be made. These tradeoffs are broken down into five primary areas: channel capacity, communications security and integrity, system integration, co-site interference implications, and networks and data latency. The trade space of most interest is the data capacity of the links. The communication system design should provide the highest data capacity possible, especially for the imaging sensors downlink, while maximizing the LPI and AJ characteristics of the link. Security measures ranging from antijam to Low Probability of Intercept (LPI)) are also of central importance to this system, especially for the Command and Control (C2) link. This is due to the expected proximity of the aircraft to jammers on a typical mission.

Latency is another key component that comes into play, especially during the targeting and weapons delivery. Latency is also important in ground operations, particularly in situations where both manned aircraft and UTAs are operating from the same airfield at the same time, and the UTA pilot must maintain situational awareness. While many aspects of the UTA mission can tolerate several seconds of time delay for transmission between the control station and the aircraft, other aspects can only tolerate seconds or tenths of seconds delay. Closely tied with latency is the ability of the control station to control more than one aircraft while not being overloaded by the influence of data from all the aircraft. The UTA system must be designed to handled these high bandwidth bottlenecks without effecting overall mission performance.

The external communications (between control station and other theater information entities) provides a significant advantage over today's aircraft. By being able to provide the pilot in the control station access to all pertinent intelligence, targeting and support data in real time, the UTA pilot will have significant advantages over today's pilots who have access to only a limited amount a real time intelligence due to narrow communication links and the amount of information which they can handle while flying the plane. The external communications will provide the capability for the receipt of intelligence data for mission planning/updating, dissemination of data, interfacing with other military components for coordinated missions, and varieties of real-time command and control and force coordination.

In order to have to have a robust UTA system, there are several technology areas which must be further developed. Airborne communications networking technology is fundamental. The UTA networked system must be able to automatically route data between all the aircraft, control station(s) and support assets while being able to dynamically allocate bandwidth (from several hundred bits/sec to several hundred kbits/sec), and to automatically prioritize data sets for aircraft that are in a combat state. This prioritization is important due to the latency encountered in either networked or SATCOM links.

Software radio technology is the emerging communications topic which apparently offers most promise for UTA. Current research indicates that software-configurable multimode digital radios will enable inherent networking capabilities plus a flexible approach to choosing the operating point in range-antijam margin-low probability of intercept margin space most appropriate to UTA systems. Compatibility with SATCOM, LOS and relay modes of operation is also important to UTA operations.

4.3 Sensors

The imaging sensors which are fielded on today's aircraft can be loosely put into two categories - reconnaissance and tactical sensors. Reconnaissance sensors usually have extremely high resolution and narrow field of view (FOV) and will often have some kind of line scan capability into order to increase the scan coverage. The tactical sensors are produced in much larger quantities, have several FOVs in order accommodate both targeting and navigational capability, and are designed to operate at much closer ranges than reconnaissance sensors. Neither existing kind of sensor may ultimately be ideal for UTA, although the basic sensor requirements (range, resolution, FOV, update rates, and so on) will continue to apply to UTAs performing the same missions as conventional aircraft.

The UTA will require not only the capability of current tactical aircraft (both targeting and navigation) but a new sensor

capability which can support telepresence or parts of its functional equivalent. The ultimate goal of this sensor capability might be to provide a full 4p steradian image field-of-regard around the aircraft which could be transmitted to a control station. This would enable true telepresence, including "off the platform" views with the potential for unique tactical perspectives. Practically speaking, true 4p will not be needed; sensor coverage can be concentrated along the waterline plane and in the forward quadrant.

The basic idea of such a sensor system would be to distribute a number of small sensors (six or more) around the aircraft. The data from all the sensors would then be combined to form a single seamless image. This data could be used for situational awareness around the aircraft and would also be utilized in air-to-air combats. An additional capability of this telepresence sensor system is to process the data on board the aircraft such that it would perform as a search and track system. While this concept is not new, only very limited portions of the research and development and engineering have been done to actually implement this sensor capability in an aircraft. Furthermore, current efforts are limited to pure EO or IR systems; ultimately there is no reason the UTA system should not be multispectral and range from EO through IR and the RF bands to provide both resolution and range capabilities for the tactical arena. Note that a true multispectral sensor suite would impose new kinds of demands on data processors, for example ATRs and data fusion and compression algorithms which are not well-suited today to deal with multispectral data of this type.

4.4 Information Fusion

A virtual manned interface will inevitably be inferior to a real cockpit interface if the only information to be used in performing the mission is data developed by onboard aircraft sensors (which includes the pilot's visual out of cockpit sensor). Not all the data can be sent back over constrained communications channels, and there will always be some latency. For the virtual pilot of a UTA to be as effective - or more effective - than a real pilot in the cockpit some other factor has to be present.

Locating the virtual control interface remote from the cockpit offers the opportunity to fuse many sources of information which can be made available on the ground (or in a ship or large C2 aircraft) but which generally cannot be sent to the cockpit. As the theater integrated information environment expands, supported by backbone communications with ultra-high data rate (e.g. SONET/ATM land lines and SATCOM links and the direct broadcast Global Broadcast System) unprecedented amounts of archived and real-time information will be available on the theater network. This can be exploited in its entirety by a virtual control interface, minimizing the amounts of data which must be exchanged with the vehicle itself. This will be an important factor in making UTA feasible and limiting the cost of its systems, particularly communications and sensor systems. The value of sending targeting information to the cockpit of a manned aircraft has been demonstrated; it remains to show that the vastly increased amounts of information available to UTA pilots will result in large increases in their performance.

4.5 Compression and Automatic Target Recognition

The goal of the UTA effort is to perform a significant portion of the sensor data processing (ATR) on-board the aircraft and disseminate only limited portions of the data to the decision makers. Consideration must also be given to the fact that some of the data which will be down linked from the aircraft may be processed by other sources or just viewed by a photo-interpreter, each of which requires unique compression considerations. In the past, most compression algorithms have been developed with the human observer as the final user. This required the compression algorithm to focus on maintaining the low and mid frequency components of the imagery while throwing away the high frequency components. Most ATRs operate on trying to find the edges of targets (i.e. the high frequency components) which is just the opposite of many current compression algorithms. Much work has been done in the area of sub-band decomposition (i.e. wavelets) compression which overcomes the dilemma of having a variety of compression requirements. Sub-band decomposition allows for a very straightforward way to isolate the information in the image in both the spatial and frequency domain simultaneously. To summarize, for the UTA effort there will be two primary compression issues for image data which must be addressed. The first is to be able to optimize compression for either a human operator or the ATR within a single band and secondly is to be able to optimize compression for multi-spectral data. All this must be done in real time.

Other unique compression processing techniques will also be considered such as Region of Interest (ROI) compression and progressive transmission. ROI compression is implemented by compressing a small portion of the image at a low ratio (e.g. 2:1) in order to maintain detail while the rest of the image is compressed at a much higher ratio (> 40:1). This technique allows for much higher compression ratios which results in faster transmission times while maintaining target detail and enough background information for situational awareness.

4.6 Airframe and Propulsion

An airframe which is built from scratch as a UTA will not be designed or built in the same way as a conventional tactical aircraft with the same general performance characteristics. This is a direct result of the lifecycle concept of operations and the elimination of the pilot from the system. This presents opportunities for innovative and affordable design concepts in a vehicle whose performance could be very high compared to piloted designs. The opportunities will be significant but will necessitate supporting technology development to enable an effective design.

Propulsion system technologies will be stressed by UTA in the event super-maneuverability is desired in the operational system. Current engines can sustain about 15 g's based on the inherent strength of engine casings and mounts and design of rotating equipment and fluid delivery systems. Lifetime at this acceleration level is likely to be limited. Technology developments will be needed to produce an engine which is sufficiently robust to enable the maneuverability of UTAs to reach maximum potential.

High instantaneous or sustained maneuvers about all axes will enable a UTA to be highly survivable in hostile environments and to employ weapons in unique ways. It will also stress engine inlets, exhausts, and air handling systems and create difficulties in ensuring continuous operation of the engine at high thrust levels. The external and internal design of propulsion installations for highly maneuverable UTAs may be fundamentally different than that of conventional aircraft.

A neglected area of military propulsion technology is adaptation of the commercial technologies and design philosophies which are producing affordable high performance engines for commercial aircraft such as business jets. Early in the U.S. Tier II+ program it was recognized that an affordable design could only be achieved by using one of this emerging family of engines; all existing military turbines would have made the vehicle acquisition cost exceed program threshold. If UTA could be designed to use a variant of a commercial engine with good specific performance its affordability would be assured.

Innovations in structural design techniques and structural materials will be very important to UTA's potential for reduced size, weight, and acquisition cost. A reduced flight hours lifetime will allow structures to be designed more for strength than for flexibility and tolerance to a high number of fatigue cycles. Aeroelastic effects may be much less significant for UTA than for conventional aircraft. Layout flexibility will allow new placement of aircraft systems and subsystems. The structure for such an aircraft may be much simpler in design and manufacturability than conventional structure - for example, skin-stiffened composite primary structures with extensive use of foam cores. These technologies would lead to revolutionary decreases in airframe cost but would require supporting developments - for example, all-electric aircraft systems with no hydraulics and avionics and sensor architectures without data buses, integrated as local area networks and providing the needed flexibility in locating components around the new structure and providing maintenance access in new ways which reduce airframe costs.

Using a "fly-by-light" or other network oriented-avionics architecture will likely be required by UTA in order to achieve "wooden round" readiness. This kind of system, complemented by appropriate computing and software architectures would allow the systems of aircraft in storage "baggies" to be accessed, exercised, diagnosed, and upgraded without removing the physical aircraft from storage. It would allow system component upgrades over the lifetime of the aircraft to be developed, integrated, and tested without requiring physical access to the aircraft, and to be installed simply by plugging into the onboard net. Some of these technologies are currently under development, but more understanding, development, and testing will be needed to understand and fulfill UTA avionics requirements. This is likely to be critical to the ultimate success of the concept, since the high maintenance burden of avionics systems cannot be compatible with the basic rationale of the UTA.

Since UTA vehicles will be stored for much of their lifetimes, it will be critical to avoid hydraulic systems. The goal should be to achieve a "dry" airframe except for fuels and lubricants which are required for the propulsion plant. The "all electric" UTA will be significantly easier to maintain and activate and will require less skilled maintenance over its lifetime than an airframe with hydraulic systems. This is a key to an affordable UTA system.

A summary of key technologies for UTA is presented in Table 1.

5.0 SUMMARY

In summary, the Unmanned Tactical Aircraft concept has the potential to become a new type of general purpose tactical aircraft system with characteristics which are distinctly different than conventional piloted aircraft, cruise missiles, and UAVs. UTAs have the potential to bring unique elements of effectiveness and affordability to the air forces which deploy them. They will be able to perform missions which are difficult or inadvisable with piloted aircraft; achieve dominant performance in some aspects of air operations on the modern battlefield; leverage emerging breakthroughs in theater information availability; and break the cost paradigm which is making it increasingly difficult for Western nations to field and maintain full tactical aircraft force structures under budgetary constraints. Because of these characteristics, it seems that UTAs will be mix cost-effectively with piloted aircraft in air force structures of the future if the technology bears its promise.

In the early stages of its development UTA will be an excellent system to demonstrate the leverage that can be obtained with a relatively small number of specialized systems. This is an emerging precept of high technology warfare - a small number of highly specialized and highly capable systems can have a disproportionate effect against an unprepared enemy. This was demonstrated in the Gulf War by the F-117, whose capabilities and unique characteristics multiplied the effectiveness of conventional forces. Even a small force of UTAs in the early deployment period holds the promise of this kind of leverage.

UTAs will have inherent limitations due to their basic control concept. The contributions made by pilots in their cockpits at the scene of the action have always been an important part of air warfare and will continue to be so. UTAs may ultimately be ill-suited to the most dynamic missions where the pilot's awareness of the situation is central to effective combat. On the other hand, UTAs may eventually be more effective than piloted aircraft where onboard tasks can be automated and the focus is on integration and exploitation of target information, most of which is available from offboard sensors in real time. UTA operations will be highly compatible with standoff weapons with organic sensors; with the emerging family of Global Positioning System guided weapons; and with beyond visual range air-to-air weapons and sensors. UTA operations will be less compatible with short range and general purpose weapons, which still require pilot skills for effective employment. How far UTA will go in emulating or exceeding the performance of piloted aircraft will depend on the balance between the limiting factors and the new elements of effectiveness inherent in the technologies; this awaits development and demonstration of the system.

Despite limitations and development problems it is worth noting that critical UTA technologies closely parallel the highest priority technology developments in other areas of tactical warfare, particularly in communications and information dominance for the integrated theater of war. Thus it

is reasonable to expect that UTA development will not stand alone - it will be accelerated as new breakthroughs are achieved in pervasive information warfare. In the history of military technology development this kind of synergism between related systems generally presages success when the basic technology concepts are sound. This factor is very favorable for UTA.

UTA is not only a concept for the far-term. Many of the enabling automation and information technologies needed for UTA currently exist and are being used in other military and commercial aircraft systems. The first UTAs could be operational in 5-10 years performing a limited set of missions. Additional technology development will be required for UTA to meet its full promise. This will probably not be achievable until the 10-20 year time period. The concept will necessarily evolve over this entire time period as new technologies become available and the user community learns how best to operate UTAs and integrate them into the force structure as a whole.

APPLICATION	TECHNOLOGY AREAS
System Control	Telepresence and virtual reality displays; 2D and 3D high resolution displays; situation awareness decision aids; natural language processing; automated mission planning; distributed interactive simulation for training/rehearsal; pilot interface human factors; intelligent variable autonomy control architectures
Communications	Multiband multimode (software) radios; spread spectrum AJ/LPI waveforms; high dynamic bandwidth airborne network protocols; agile beam conformal antennas; network security
Information Fusion	Multispectral image fusion; automatic target recognition and counter CC&D algorithms; IFFN phenomenologies; intelligent filtering and correlation algorithms; targeting and target system analysis decision aids; object-oriented data bases and data accession algorithms
Data Compression	Multispectral compression algorithms; RT hardware implementation of algorithms; compression algorithms designed for both images and ATR processing; automated region of interest compression
Sensors	Distributed aperture EO/Imaging IR sensors; uncooled IR detectors; focal plane arrays; smart active skins (RF); onboard ATR implementations
Aircraft Control	Adaptive autonomy management; multispectral image fusion; intelligent planning and routine algorithms; signature management systems; intelligent defensive maneuver planning
Airframe and Propulsion	Ultra-high "g" designs and materials for turbomachinery and flow systems; airframe materials for UTA lifetime profile; advanced structural design techniques; thrust vectoring; all-electric systems designs and components (replace hydraulics); signatures technologies; fly by light avionics components; networked avionics architectures and components; storage technologies (baggies, preservants, ...); EO/IR/RF aperture designs and components

Table 1. Summary of Key Technologies for UTA

Several individual technologies will be key to this development. These are critical for UTA but for the most part are also important for other tactical aircraft as well. However, the most important challenges are in the area of system integration - for UTA cannot perform well in any time period unless the system is thoughtfully integrated into a complete combat system. To this end the involvement of users in conception, development, and demonstration of the UTA will be essential as it evolves. Although some resistance to the concept may be expected from the pilot community, ultimately it will be accepted, for UTA preserves the role of the pilot more so than other unmanned systems (such as advanced cruise missiles) and complements operations of other piloted systems. This acceptance will be critical, because UTA cannot be imposed on tactical air forces and will not be effective without their direct participation in development.

Airborne and Spaceborne SAR Systems: Possibilities and Limitations for Military Use

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1. SUMMARY

Synthetic Apertur Radar (SAR) is perfectly suited for aerospace surveillance and reconnaissance systems. In principal, SAR combines the advantages of microwave systems like weather independence, optical visibility, penetration capability. The state of the art as well as the development of technique and technologies needed and possibilities of future systems will be shown briefly.

2. USER REQUIREMENTS

The development of innovative SAR technique and technology is based on the requirements deriving from the use and application of such systems. Military users mainly require special parameters on specific objects to be observed identified and classified. These requirements lead to specifications for special electrical and geometrical SAR system parameters. Principally, military user require so called "superb information" which are [1]:

- detect, locate, track and identify, anywhere in the world ground as well as naval forces (tanks, guns, trucks, trains, helicopters, aircraft, missiles, ships etc.).
- conditions: day or night, cloudy or clear,. targets moving or non-moving, all types of terrain, foliage cover, camouflage, and decoys possible,
- need very timely coverage (often continuous coverage) as well as need wide-area coverage (e. g. a full theater of operations such as all of Iraq),

This entails mainly the following more technical requirements:

- frequencies between HF and Ku-band,
- high geometrical and radiometrical resolution,
- wide swath,
- real-time processing and data evaluation,
- MTI capability.

In addition, low cost systems are required which are lightweight, small and easy to handle and to install. A further important issue for the design and development is the platform for these SAR systems. Both, spaceborne as well as airborne platforms have to be taken into account. Both carrier systems are complementary to each other.

Satellites offer the possibility to reach each area around the globe even such aeras where aircraft overflights are denied. Permanent coverage can be principally obtained with a system contenting more than one satellite and with defined inclinations. Exemplarically, 20 satellites on 3 different orbit planes at an altitude of about 1800 km would allow a continuous global coverage. However, this would lead to extremely high power requirements as well as to extreme costs. These facts underline the need for low cost systems (presently, the costs for a radar satellite are between 500 millions and 1 billion Dollars or more).

Airborne systems are much better suited to both the requirements for frequent observation repetition and the low cost requirements. Airborne radars, principally, can be substanially less expensive than spaceborne systems. Particularly, both long-endurance, high-altitude Unmanned Air Vehicles (UAV's) as well as low flying Remotely Piloted Vehicles (RPV) are preferable platforms beside conventional aircraft. UAVs like the Boeing CONDOR can carry SAR payloads for more than 100 hours at an altitude of about 23 km. CONDOR represents the state of the art as well as the TIERS II programm of ARPA [2] which is presently under consideration. This system consists of 4 UAVs and one groundstation and would be able to provide continuous coverage of a major regional area for a period of 30 days. The UAVs should carry a SAR with the observation capability of about 100 000 km^2 per day. However, the large figure of airborne platforms require for a large number of lightweight and low-cost SAR. 10 millions USD each for large production

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quantities presently is a very ambitious goal.

3. BASICS OF SAR

The most important equations which combine different SAR parameters are given in Table 1 [3,4]. Some specialities of SAR become evident. The azimuth resolution of a SAR is independent of wavelength and distance and a better resolution can be reached with smaller real antennas and not with larger antennas. This is opposite to real aperture radars and optical systems. For SAR the theoretical limit of azimuth ground resolution is given by the half antenna length in flight direction. These equations also establish principal technological limits for the development and applications of spaceborne

1	Point Target S/N	$\frac{S}{N} = \frac{P_{ave} A^2 \sigma}{(4\pi)\lambda^2 R^3 (kT_o F) 2v \delta_{az}}$
2	PRF	$2v/D \leq (PRF) \leq c/2R_{max}$
3	Slant Res. (δ_{rg})	$\delta_{rg} = c/2B = c\tau_p/2$
4	Opt. Az. Res. (δ_{az})	$\delta_{az} = D/2$
5	Swath S	$S = c\, D/4v$
6	Synthetic Aperture Length (L)	$L = \lambda\, R/D$
7	Az. Pixel Nr. (N_{az})	$N_{az} = R\lambda/2\, \delta_{az} = L/\delta_{az}$
8	Range Pixel (N_{rg})	$N_{rg} = S/\delta_{rg}$
9	Data Rate (DR)	$DR = N_{rg}\, PRF$
10	Pixel Rate (Q)	$Q = nvS/\delta_{az}\, \delta_{rg}$

A = Antenna Area, B = Bandwidth, c = Light Velocity, D = Antenna Length, kT_oF = Noise Characteristic, n = Number of Looks, P_{ave} = Mean Power, PRF = Pulse Repetition Frequency, R_{max} = Maximum Distance SAR-Pixel, v = Platform Velocity, λ = Wavelength, σ = Radar Cross Section, τ_p = Pulse Length

Table 1 Important Relations for Strip Map SAR.

3.1 Resolution

Resolution in a wide sense is defined as the discrimination capability of a sensor considering two targets with equal properties (geometric properties, colours, velocities, frequencies etc.). In table 2 requirements for different sensing grades (detection, recognition, identification, description) of special objects are listed [5]. Geometric resolution requirements, however, entail requirements for the bandwidth of a SAR system and the bandwidth is a technological key parameter for SAR realisation. For detection, recognition, and identification of landmine fields, for example, resolutions between 9 m and 0.9 m are required, corresponding to bandwidths between 17 MHz and 170 MHz respectively which are realizable. For description, however, a resolution of 2.5 cm is required which entails a requirement for 6000 MHz bandwidth, a rather extreme bandwidth, exspecially for spaceborne SAR which is presently not realiable. Expecially, for imaging systems like SAR, the angular resolution is strictly connected to the radiometric resolution.which in SAR images is dependent on the image statistic, the speckle. By increasing the integration time (i. e. the observation time of a certain area respresented through the number of looks on it) the speckle will decrease, the radiometric resolution increases (the image beomes sharper) but the angular resolution decreases.

3.2 Choice of Frequency and Polarisation

The choice of frequency for SAR systems depends on many factors. Atmosphere and ionosphere produce attenuation and frequency dependent distortions and errors as well. These effects set an upper limit due to attenuation for spaceborne radar at about 15 GHz and a lower limit for spaceborne SAR due to ionospheric granularity at about 1 GHz. Interferences with Earth bound communication links and surveillance radars set also a lower bound to about 1 GHz. Signal to noise ratio as well as ambiguity considerations seem to prefer the X-band for spaceborne military purposes. The available frequency bands are also limited due to international contracts. The reflection behaviour of radar targets is strongly frequency dependent also, and therefore, multifrequency systems are required in order to increase the information content of the respective observation.

In principle, a complete description of a radar target can be given only if all copolar and crosspolar amplitudes and the respective phase of the radar signal are

Object	Detection		Recognition		Identification		Description	
	Res (m)	BW (MHz)	Res (m)	BW (MHz)	Res (m)	BW (MHz)	Res (m)	BW (MHz)
Military Airfields	60	25	1.7	90	4.5	33	1.5	100
Urban Areas	60	25	30	5	3	50	3	50
Ports	30	5	15	10	6	25	3	50
Bridges	6	25	4.5	33	1.5	100	0.90	170
Roads	9	17	6	25	1.8	83	0.6	250
Air Base Equipment	6	25	4.5	33	3	50	0.30	500
Troop Units or Bivouacs	6	25	2.1	71	1.2	125	0.30	500
Artillery and Rockets	0.9	170	0.6	250	0.15	1000	0.05	3000
Medium Surface Vessels	7.5	20	4.5	33	0.6	250	0.30	500
Land Mine Fields	9	17	6	25	0.9	170	0.025	6000
Aircraft	4.5	33	1.50	100	0.9	170	0.15	1000
Vehicles	1.5	100	0.6	250	0.3	500	0.05	3000

Table 2 Resolution (Res) required for different sensing grades for special objects [4] together with the resulting bandwidth (BW) using the simple pulse length-bandwidth relation (3) in Table 1.

known. Such a "complete radar" gives all information on a target possible within the relative small bandwidth of the radar carrier frequency, it should be equipped with more than 1 channel in order to register the likepolar amplitudes, the crosspolar amplitudes as well as the respective phases. This implies not only a tremendous expense but also large technical difficulties with respect to data rates.

3.3 Power Considerations

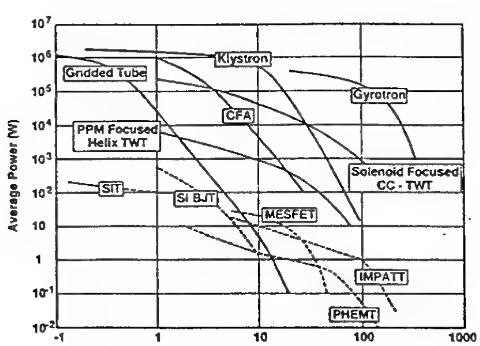

Fig. 1 Peak transmit power for RF sources vs frequency, circa 1993 [6], ___ vakuum devices, ---- solid state devices.

The transmitter power is also a key element for radar design. The main transmitter power estimates and limits to some extent the distance from which a radar observation to a certain target can be successfully made and, therefore, the orbit altitude of a reconnaissance system is power limited. Principally, the power required increases with the 3rd power of the radar distance [Table 1]. In any case, the transmitter power is a limiting element for the design of a SAR as well as the antenna. Todays state of the art are a few hundreds watt mean power [Fig. 1] [6] and a few kilowatts peak power. This entails requirements for the total power supply of a satellite. State of the art is here an amount of 6 KW to 10 KW as a maximum. These requirements can be fulfilled with solar power generators and atomic generators as well and, principally, with a large figure of transmit/reiceve modules in active phased arrays.

3.4 Antenna limitations

The antenna is a key element which also estimates the capability of SAR systems. In almost all basic SAR equations the antenna dimensions occur. The antenna defines and influences respectively

- the receivers S/N by its area (gain),

- the along track resolution by its length,
- the swath width by its length,
- the across track resolution by its bandwidth,
- the ambiguity suppression by its sidelobes,
- the required onboard power by its area (gain),
- the polarimetric performance by its polarisation,
- the data take opportunity in ScanSAR and spotlightSAR by its beam steering,
- the surveillance capability by its length.

For airborne SAR the antenna dimensions, principally, are limited due to the size and shape of the platform. Due to its relatively low level (compared to spaceborne SAR) small antennas are more promising. The antenna dimensions for spaceborne SAR are at present of about 15 m x 1 m for microstrip array antennas (Radarsat). Mirror antennas for space applications can be larger.

The antenna also limits the SAR surveillance capacity fundamentally. Fundamental restrictions of the area coverage rate Å can be deducted from equation (2) and (5) in Table 1. Therefore results

$$\dot{A} = \frac{dA}{dt} = R_{\max} \cdot v < c \cdot \frac{D}{4} .$$

For an antenna of 10 m length, used for SIR-C/X-SAR , for instance, results a maximum area covering rate

$$\dot{A} < 750\ km^2\, s^{-1} .$$

A velocity of 7.5 km s^{-1} (corresponding to an altitude of about 300 km) leads to a maximum swath of about 100 km which can be observed with a 10 m antenna. This rough estimation is in good agreement with the measurements made during the SIR-C/X-SAR missions.

3.5 Data Rates and Processing Requirements

SAR systems produce a tremendous amount of data. Requirements for high resolution and large swath widths make the data rates higher as far as the resolution becomes finer and the swath width becomes wider. All requirements for extensions of SAR to multifrequency , mulipolarisation or multi-incidence capability additionally entail a multiplication of the data rates and this would exceed the present limitations of data handling. This is a key problem in all SAR considerations. Therefore, different requirements have to be fulfilled in order to handle or reduce the data stream of future systems either by means of onboard processing or with development of new SAR systems like stretchSAR etc. The capacity of data links must be increased. New data transmission systems with splitted data links to data relay satellites or ground stations respectively are under preparation. The carrier frequencies of these data links have to be increased up to a maximum value in order to obtain large bandwidths. (X- or Ku-band)

Data storage capability also has to be increased. At present, recorders with capabilities exceeding 40 Gbyte are suitable for use in space. The present state is, however, to use more than one recorder, i. e. one recorder for each channel in multipolarisation and multifrequency SAR.

State of the art for data handling (transmission and storage) are at the moment bitrates of about 240 Mbit s^{-1}. Real-time SAR processing requirements lead to extreme requirements for the computer processor power (M flops) as well as to requirements for the respective computer memory (MB).

Conventionally, the so-called data rate DR is addressed which is definded in (9) from Table 1. However, for the processor sizing the total computation load has to be considered which takes the different operations that have to be done with each sample into account (range compression, corner turn, azimuth compression etc.). Therefore, the processor size required is proportional to the pixel rate Q (10 in Table 1) multiplied with the number of operations per pixel per look [7, 8]. These considerations lead to the following expressions for the processing rate PR:

$$PR = kn \frac{v \cdot S}{\delta_{az} \cdot \delta_{rg}}$$

The processor memory that is necessary, (MR), depends direcly on the pixel number within the processing frame. The latter is proportional to the product of number of pixels in azimuth N_{az} times number of pixels in range N_{rg}. For MR holds [7]

$$MR \approx 10\, n^{2} \cdot N_{az} \cdot N_{rg} = 10\, n^{2} \frac{s}{\delta_{rg}} \cdot \frac{L}{\delta_{az}}$$

$$MR \approx 40\, n^2 \frac{S \cdot R \cdot \lambda}{\delta_{rg}\, \delta_{az}^{\ 2}}$$

Remarkable is the inverse proportionally to the cube of resolution and the proportionality to both radar wavelength and image range. For Radarsat, ERS-1 and SIR-C/X-SAR, the resulting processor loads and processor memory requirements are given in Table 3.

	X-SAR	ERS-1/2	RADARSAT
Looks (n)	4	4	1
Swath (S)/km	45	80	50
Range (R)/km	436	844	1277
Velocity km/s	7,7	7,5	7,5
λ/m	0,03	0,06	0,06
δ_{az}/m	30	20	9
δ_{rg}/m	10	10	9
PR/ Gflops	2,3	6,0	2,3
MR/GB	3,0	2,5	1,5

Table 3 Processor Load (PR) and memory requirements (MR) resulting from specifications from SIR-C/X-SAR, ERS-1/2 and RADARSAT.

An increase of resoultion with respect to some requirements in Table 2 would entail a dramatic increase of processor and memory requirements. Computational requirements of this magnitude currently cannot be met neither by a single processor nor by processor network. Therefore, real-time processing for these purposes at the moment is not possible with spaceborne SAR. The capability limits of micro-processor chips today available for real time processing are: processing power = 150 Mflops, Memory = 4000 MB [7].

4. PRINCIPAL PENETRATION CAPABILITY OF MICROWAVES

An advantage of microwaves in comparision to electromagnetic waves in optical wavelengths is their penetration capability. However, a reasonable penetration depth into seawater cannot be reached with microwaves at all. In the frequency range between approximately 100 MHz and 200 MHz a reasonable penetration depth into dry and wet land seems to be possible (between 1 m for wet ground and several 10 m for very dry ground). Vegetation has a lower density than soil and this enables generally a better penetration into rough vegetation like foliage, bushes and crop than into solid landsurfaces. However, penetration increases with increasing wavelength. In connection with high resolution requirements, this requires ultra wideband low frequency systems.

5. SPECIAL MODES AND TECHNIQUES

Normally, present SAR systems use the **strip map mode** (chapter 2). Very fine resolution can be achieved for relatively small scene size using a **spotlight** SAR for specialised missions. **ScanSAR** systems have the ability to cover wide areas (up to 500 km swath) at lower resolutions and higher repetition rates (SIR-C has a ScanSAR mode). The trade-off between radiometric and geometric resolution is very often in conflict with military user requirements which need both, high geometric as well as radiometric resolution. For this purpose, the so-called **look-steering mode** is under consideration. The principals of these different modes are compared in figure 2.

5.1 SAR Interferometry

SAR interferometry, mainly is a technique for rapid and accurate collection of topographic data, which is essential for establishing digital elevation models. Coherence measurements which are principally essential for interferometry allow change detection as well and herewith special man made target detection. Normally, interferometry works with two antennas separated in cross velocity direction. The distance between the two antennas is the so-called baseline. State of the art is two-path interferometry with spaceborne SAR, and altitude accuracy of about 10 m (ERS-1/2, SIR-C/X-SAR). Single pass and two pass interferometry with airborne SAR has accuracies of 0,1 m up to 1 m. With differential interferometry accuracies in the cm range have been obtained with spaceborne and airborne SAR. The following formulas describe the principally altitude accuracy δ_z reachable theoretically with a baseline B in a distance R and a given phase accuray δ_φ for vertical across track antenna positions and an incidence angle ϑ.

Normal Interferometry:

$$\delta_z \approx \frac{\lambda \cdot R \sin \vartheta}{2\pi B} \delta_\varphi .$$

Differential Interferometry:

$$\delta_z \approx \frac{\lambda}{4\pi} \delta_\varphi$$

The latter formula points out the tremendous accuracy which can be reached. Technically feasable is $\delta_\varphi \geq 5°$ which leads to a theoretical accuracy of 0.007λ. This points out why accuracies of better than 1 cm have been reached against point targets with spaceborne interferometry.

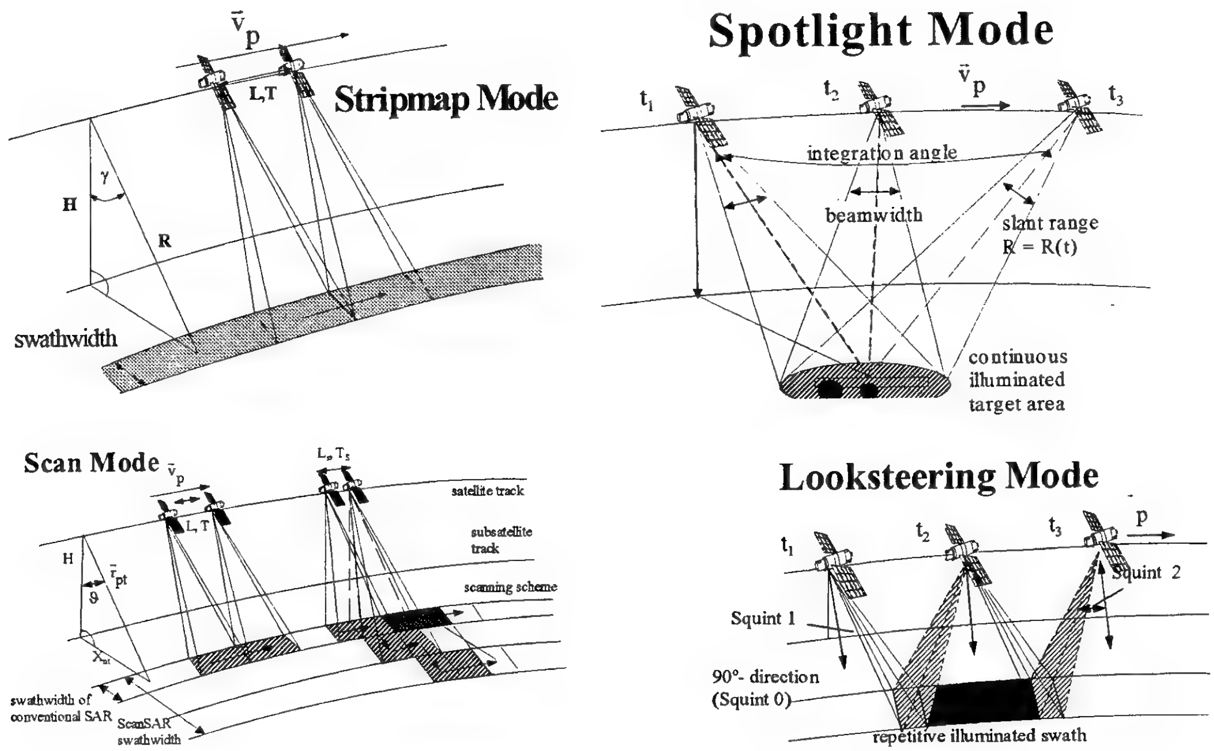

Figure 2 Schematic and principal representations of different SAR modes

5.2 MTI Possibilities of SAR

SAR, principally, has the ability for moving target identification which is for military users very often both a strategic and tactical requirement. The methods described in [10 to 15] represent the state of the art of MTI with SAR.

6. SPECIFIC MILITARY SAR APPLICATIONS

Under these technical and technological conditions, SAR will be applied for the following military missions [19]:

- Wide area surveillance as well as reconnaissance and battle damage assessment from both airborne and spaceborne platforms using ScanSAR and stripmap SAR.
- Air to ground targeting and fire control mainly with airborne stripmap and look steering modes. For one of the main tasks namely to accurately deliver munitions, SAR with very high resolution (dm-range) and alocation accuracy of better than 10 m is necessary. This leads to requirements for bandwidths > 1 GHz and probably X-band frequencies or even higher.
- To find theater of both ballistic and cruise missiles with airborne SAR using more or less all available modes.
- Concealed target detection as well as detection of underground facilites mainly with low frequency airborne SAR using different modes. Ultrawide band SAR frequencies between 20 MHz up to 600 MHz are necessary associated with significant onboard processing. This requires ultrawide band antenna structures (up to 100 % band-width) as well as high power. Intelligent signal processing is necessary in order to detect not only the required objects itself but also secondary signatures as roads, entrances, power cabeling etc. Furthermore, fusion with other data than SAR seems to be indispensable.
- Automatic naivagation of missiles and low flying manned as well as unmanned vehicles using digital elevation models established by airborne and spaceborne SAR interferometry. Height accuracy < 1 m is required.
- Moving target indication with special airborne stripmap MTI modes.

The use of multipath SAR interferometry (2 or 3 passes) in connection with special signal processing allows detection and measurement of subtile changes which can neither be detected by human eyes nor by conventional SAR information. However for military purposes SAR is not a stand-alone technique. In most of these applications, data fusion with other sensor data obtained in optical wavelenghts for example, are mostly helpful and sometimes indispensable for all these applications. A high degree of precision is always necessary in order to support spatial and temporal correlation and the fusion of multisensor data. A high degree of calibration is also an important requirement.

7. STATE OF THE ART SUMMARY

Key radar systems features are frequency, polarization, transmitter/receiver approach and beam steering capability. Main areas of SAR technology are: antenna, RF electronics and data processing as well as data evaluation and interpretation. State of the art are phased array antennas with distributed transmitter/receiver modules. Especially size and weight are critical for spaceborne systems (the total mass of the radar electronics plus the antenna for both, SIR-C/X-SAR and RADARSAT, is about 9000 kg). An extremely high effort for data handling with respect to processing and evalutaion features is necessary. The SIR-C subsystem for data handling for instance is 145 kg in weight and consumes about 800 W power. Image data processing capabilities are limited also. The X-SAR processor, for example, needs at present about 35 minutes to process one scene. Resolution requirements estimate the processing load as well as memory requirements. Especially for spaceborne SAR, this leads to extremely large figures which can not be realized at present.

The SIR-C/X-SAR system flown twice onbord the space shuttle in 1994 is the most modern of todays spaceborne systems [16]. It works in X-, C-, and L-band, in the latter two ranges it has full polarimetric capabilitiy. Therefore, it has 7 independent channels, the data rate for each is 45 Mbit/s. The hightest resolution obtained is < 10 m. In L- and C-band it has a phased array antenna with distributed power modules. This enables electronic beam steering for special modes like ScanSAR in order to extend the swath width. All the other actual civil spaceborne systems (ERS1, J-ERS-1, ALMAZ-1, RADARSAT) have one polarization mode only. RADARSAT has a maximum data rate of 110 Mbit/s. All civilian spaceborne systems use groundbased data processing. Actually, a data link capacity of 200 Mbit/s is possible. Recorders qualified for use in space, at present, have a data storage capability exceeding 40 GByte. The present approach is to use more recorders, one for each channel as in SIR-C/X-SAR. Here, processing loads up to 6000 Mflops have been reached. Real time processing with high image qualitiy was therefore not possible.

Especially with respect to resolution as well as to real time processing the todays capabilities of airborne SAR are principally more sophisticated. Geometric resolution in the dm range is state of the art as well as real time onboard processing. There exist world-wide about 30 experimental airborne SAR systems [17]. Exemplarically named should be here ERIMs Isphare (X-band polarimetric with high resolution interferometry) as well as its foliage penetration FOLPEN-SAR. The latter is comparable to the Swedish CARABAS which is working in the frequency range between 10 MHz and 100 MHz as well. The German Do SAR (Dornier) also has resolutions in the dm- range. Aerosensing's AERS-1 has obtained interferometry accuracies in the cm-range. DLR's E-SAR covers frequencies in P-, L-, C- and X-Band and is an example for fixe mounted antennas [18].

New SAR modes are on the brink of leaving the experimental state. Very fine resolution can be achieved for relatively small scence sizes using spotlight SAR for specialized missions. ScanSAR systems used in SIR-C as well as in RADARSAT have the ability to cover wide areas (up to 500 km swath) lower resolutions and higher repetition rates. For SAR interferometry the state of the art is two pass interferometry with spaceborne SAR and altitude accuracies of about 10 m (ERS-1/2, SIR-C/X-SAR). One pass interferometry for a third SIR-C/X-SAR mission is under preparation. Single pass and two pass interferometry with airborne SAR has accuracies of 1 m down to 1 dm. With differential interferometry accuracies in the cm range have been obtained with spaceborne and airborne SAR as well. However, the accuracy of interferometry strongly depends on the accuracy of flight path knowledge with respect to position as well as to attitude. This is the most critical system component for airborne SAR. Highly accurate differntial GPS is indispensable for that purpose.

8. TECHNOLOGICAL EXPECTATIONS

	State of the Art	2000	2005 & beyond
Airborne Antennas	gimbal mounted high gain, gimbal steered phased array	fix mounted low gain, gimbal steered active phased arrays	conformal active arrays, steerable beamwidth
Spaceborne Antennas	active phased arrays (L, C), waveguide (X), 1000 - 8000 kg (SIR-C)	active phased arrays, compact structures, 100 kg	inflattable structures 30 kg

Table 4 Expected Antenna Improvements for the next decade

	1997	2001	2004	2007	2010	Approx. Improvement
Chip-Frequency MHz	300	600	800	1000	1900	4
Bits/Chip (DRAM or Flash)	150 M	1G	4 G	16 G	64 G	40
Chip Size (ASIC) mm²	500	750	900	1100	1400	3
Logic Transistors per cm²	5 M	20 M	50 M	100 M	300 M	60
cost/Transist or Milli cents	1	0.2	0.1	0.05	0.02	50

Table 5 Expected data electronic development with respect to efficiency, volume and costs [20]

For the further development of airborne and spaceborne SAR the following requirements exist under cost and efficiency considerations:

- mass, volume and power consumption have to be reduced (about 2 orders of magnitude).
- autonomous spacecraft as well as UAV control and operation and onboard data analysis and feature extraction should be realized.

This leads to requirements for light weight high gain antennas, high efficiency RF-conversion, AD-converters with both higher sampling rates and higher dynamic range, and low power, ultra reliable spaceborne processors. Expecially for spaceborne SAR, high efficiency and light weight solar cells must be available. In addition, special algorithms for data processing, and data evaluation as well as for pattern recognition must be developed which have to be adapted to the respective state of the art of processor technology.

The [4, 5, 6] tables summarize roughly the technology developments which are responsible for the proposed SAR system goals and which are expected to be realised during the next decade.

The main progress will be obtained in data processing, data evaluation and data interpretation for both airborne and spaceborne SAR. Onboard real time processing with automatic feature extraction will be available. The future onboard SAR processors will be small, lightweight and will consume less than 50 W power. For automatic data evaluation, feature extraction and image interpretation, the use of artificial intelligence is indispensable. This will lead to a drastic reduction in the downlink requirements also.

	1997	2002
Watt / MMIC	5 - 10	20-20
$\frac{MMIC}{mm}$ Ø	75 - 100	150
W/cm³	16	1100

Table 6 Expected Power Development (MMICs)

For spaceborne SAR ligthweight antennas will be availabe and the power efficiency of solid state devices will exceed 60 %. This, in connection with higher miniaturization, will drastically reduce the mass and volume of the RF system including the antenna down to 10 % and less. A high degree of automation of the radar and operation functions will reduce the effort for post launch mission operation. This influences the capabilities of spaceborne as well as of airborne SAR. The requirements for high repetition rates can be fulfilled with multi-satellite systems using special orbits. The high degree of automation will make the operation of SAR on unmanned vehicles possible. Helicopters also will be equipped with special SAR systems, where the antennas are mounted within the tips of the rotor blades.

New methods for calibration and error elimination will neutralize negative influences of atmospheric, tropospheric as well as ionosperic turbulences to a wide extent. This will entail an increase of resolution power, image quality, and measurement accuarcy. Additionally, it will open the possibliy to operate new very low frequency ranges for spaceborne as well as for airborne SAR. Frequencies widely below 1 GHz for spaceborne SAR will increase the penetration capability into vegetation as well as into solid surfaces.

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PAPER: B-6

DISCUSSOR'S NAME: G. Fleeman

QUESTION:

Please comment on the applicability of a SAR seeker to air-to-surface tactical missile applications. Is a SAR seeker affordable and are the weight and antenna size compatible with tactical missile constraints?

AUTHOR/PRESENTER'S REPLY:

SAR for tactical missile applications is possible especially with methods using the motion information which is within the radar signal itself. Flat and lightweight antennas can be integrated and fixed on the missile surface. Small fibre gyros and GPS can be used as an additional support. In C-Band, for example, with a fixed 20cm dish an azimuth resolution of 50cm has been obtained with 50W peak power from a small D0225 aircraft.

TECHNIQUES A BANDE ULTRA-LARGE ET APPLICATIONS

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1. SOMMAIRE

L'objet de la présente communication est de présenter en forme de synthèse une introduction aux radars à bande ultra-large et à leur technologie. Après définition et précision de la terminologie propre à ces nouveaux radars, on décrit la forme des signaux qu'ils émettent en les comparant dans les domaines temporel et fréquentiel à ceux qui sont émis par les radars classiques. On passe ensuite en revue les divers types d'émetteurs utilisables, les antennes spécifiques récemment développées et les structures possibles pour le récepteur.
Enfin, les techniques d'analyse et de traitement de signaux spécifiques aux signaux non sinusoïdaux et impulsionnels sont brièvement présentées avant de conclure sur les perspectives d'avenir.

2. INTRODUCTION

Grâce aux progrès considérables accomplis ces dix dernières années dans la conception des émetteurs, des antennes et des récepteurs à très large bande, les techniques à large spectre d'analyse et plus particulièrement les radars à bande ultra-large, suscitent un intérêt croissant auprès des laboratoires de recherche en télédétection et en imagerie à haute résolution.

Le radar à bande ultra-large, qui émet des signaux non sinusoïdaux ou des signaux transitoires sans porteuse de durée ultra-courte (<1ns) et de spectre de fréquence très large, tend à gagner du terrain lorsqu'il ne s'impose pas nettement dans des applications aussi variées que

- la détection d'objets enterrés
- l'observation au travers d'un écran de végétation
- l'identification de cibles radar non-coopératives
- la localisation de victimes d'un tremblement de terre
- l'étude de la stratification des sols
- la détection de mines antipersonnel et antichar
- la détection de cibles radar utilisant les techniques de furtivité
- la détection de naufragés en présence de fouillis de houle

Contrairement aux radars classiques qui émettent des signaux à spectre étroit, les radars UWB (de l'anglais Ultra-Wideband) émettent en effet des signaux dont la largeur spectrale relative instantanée dépasse 25 %, ce qui leur confère une aptitude particulière à la détection de cibles réputées difficiles pour les radars classiques.

Suivant la forme du signal émis on distingue différents types de radars à bande ultra-large, mais tous ont ceci en commun que l'information recherchée sur la cible détectée - sa localisation, sa nature, voire son identification - est obtenue par une analyse fine de la forme temporelle du signal reçu, alors que dans les radars classiques seule la puissance du signal détecté et éventuellement son décalage Doppler sont mesurés.

Par suite, un radar UWB ne peut fonctionner correctement que s'il est muni d'une antenne à bande ultra-large garantissant une certaine fidélité de la forme temporelle des signaux émis et reçus. En outre, l'antenne d'un radar, qu'il s'agisse d'une antenne physique ou d'une antenne à ouverture synthétique, doit nécessairement être directive pour conférer au radar sa résolution spatiale. Il est aussi souhaitable que la polarisation de l'antenne soit bien contrôlée afin de pouvoir enregistrer la réponse de la cible dans les diverses polarisations (hh,vv,vh,hv). Pour un radar UWB, l'antenne doit donc conserver ses propriétés de directivité et de polarisation sur une très large plage de fréquence.

L'objet de la présente communication est de présenter en forme de synthèse une introduction aux radars à bande ultra-large et à leur technologie. Après définition et précision de la terminologie propre à ces nouveaux radars, on décrit la forme des signaux qu'ils émettent en les comparant dans les domaines temporel et fréquentiel à ceux qui sont émis par les radars classiques. On passe ensuite en revue les divers types d'émetteurs utilisables, les antennes spécifiques récemment développées et les structures possibles pour le récepteur.
Enfin, les techniques d'analyse et de traitement de signaux spécifiques aux signaux non sinusoïdaux et impulsionnels sont brièvement présentées avant de conclure sur les perspectives d'avenir.

3. DEFINITION ET TERMINOLOGIE DES RADARS À BANDE ULTRA-LARGE

La nouveauté du concept de radar à bande ultra-large, le caractère émergent des technologies sur lesquelles il s'appuie et la variété de ses applications potentielles font que les définitions et la terminologie des radars UWB varient d'un auteur à l'autre, ce qui est parfois la source de confusion. Des qualificatifs tels que "à bande étroite" et "à large bande" prennent des significations diverses suivant le domaine d'intérêt (télécommunications, radar, guerre électronique, etc). Ainsi en matière de brouillage électromagnétique, le signal de brouillage sera considéré tantôt comme un signal à bande étroite, tantôt comme un signal à large bande suivant que sa largeur spectrale est grande ou petite par rapport à la bande passante du récepteur. Il faut savoir que la terminologie anglaise ne se limite pas au seul terme de UWB (Ultra-Wideband) mais que le même radar est aussi désigné par les vocables suivants : "impulse, time domain, nonsinusoidal, baseband, video pulse radar" ou encore "ultrahigh resolution, carrierless radar".

Aussi adoptera-t-on ici les définitions et la terminologie recommandées par la DARPA (Defense Advanced Research Project Agency) dans son rapport d'évaluation du radar UWB en 1990 [1]. Un radar est dit *à bande ultra-large* lorsque la largeur de bande relative instantanée de son signal, notée BW et définie ci-après, est supérieure ou égale à 0,25.

$$BW = \frac{2\left(F_{MAX} - F_{MIN}\right)}{F_{MAX} + F_{MIN}} \tag{1}$$

Les fréquences F_{MAX} et F_{MIN} représentent les limites du spectre entre lesquelles est contenue une proportion donnée (90 ou 99%) de l'énergie totale du signal. La notion de largeur de bande relative instantanée sert d'ailleurs à définir deux autres classes de radars : les radars à bande étroite (BW<1%) et les radars à large bande (1% <BW<25%). Cette distinction peut sembler quelque peu arbitraire et elle l'est effectivement.

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 2.

Car comment pourrait-on justifier qu'un radar ayant une largeur de bande de 0,24 n'est pas à bande ultra-large alors qu'un autre radar pour lequel BW= 0,26 le serait. Comme en toute chose, il convient de considérer les définitions données avec un certain relativisme. Mais il ne faut pas pour autant confondre un radar UWB avec un récepteur à bande étroite dont la fréquence d'accord peut varier sur une large plage. Ainsi, un récepteur de 10 MHz de bande passante accordable entre 1 et 18 GHz offre certes une très grande largeur de bande mais sa largeur relative instantanée maximale n'est que de 1%.
De même convient-il de distinguer les radars UWB des systèmes de radiocommunications à spectre étalé. Dans ces derniers systèmes, l'énergie du signal à transmettre est répartie sur une bande de fréquence plus large que la bande passante minimale nécessaire à la transmission de l'information. L'étalement est obtenu en modulant le signal à spectre étroit en bande de base - par exemple un canal à fréquence vocale de quelques kHz - par un signal de codage à large bande qui distribue son énergie sur une plus large bande spectrale (quelques MHz). Le signal modulé résultant, qui est centré sur une porteuse de l'ordre de la centaine de MHz, présente donc une largeur de bande relative d'à peine 1%.

4. FORME DES SIGNAUX EMIS

Un radar à impulsions classique émet une porteuse sinusoïdale de fréquence généralement supérieure à 1 GHz, modulée en amplitude par une impulsion rectangulaire de durée τ égale à quelques microsecondes avec une puissance de crête qui va, selon l'application envisagée, de quelques kilowatts à plusieurs dizaines de mégawatts (Fig.1a). L'énergie contenue dans l'impulsion émise est donc de l'ordre de 1 à 10 Joule. Le spectre de fréquence correspondant, qui a la forme d'un sinus cardinal, a une largeur de bande à 3 dB de l'ordre de $1/\tau$ soit environ 1 MHz pour une durée τ = 1us. La largeur de bande relative instantanée d'un radar classique est donc inférieure au pourcent.

Les radars à bande ultra-large en revanche émettent des signaux dont la largeur de bande relative instantanée dépasse 25 %. Suivant l'application envisagée et la bande de fréquence à couvrir, les radars UWB émettent l'un des signaux représentés aux Fig. 1b à 1f [2].
Le premier type de signal est une *impulsion en bande de base* (c.-à-d. sans porteuse), de durée extrêmement courte (τ < 1 ns) et dont la valeur moyenne est rendue nulle par une tension de décalage de manière à satisfaire à la condition de rayonnement (Fig.1b). Une antenne ne peut en effet rayonner la composante continue et il serait donc défavorable d'appliquer à ses bornes un signal dont la densité spectrale de puissance est maximale à 0 Hz, ce qui serait le cas d'une impulsion unipolaire non décalée (spectre en pointillé). En pratique, compte tenu des générateurs d'impulsions existants, l'impulsion rectangulaire n'a pas des fronts aussi raides mais ressemble plutôt à une impulsion gaussienne, dont le spectre est également gaussien.
Au lieu d'appliquer une tension de décalage à l'impulsion unipolaire pour annuler sa composante continue, on peut aussi concaténer plusieurs impulsions de polarités opposées suivant une séquence pseudo-aléatoire (Fig.1c). En concaténant un nombre suffisant d'impulsions, on rend la composante continue du signal résultant aussi proche que l'on veut de zéro. Outre le fait qu'il annule la composante continue, le codage permet aussi d'allonger la durée de l'impulsion ce qui augmente le facteur de charge et donc la puissance moyenne du signal. Ceci peut s'avérer utile pour les applications où la puissance de crête ne peut être produite ou serait indésirable pour des raisons d'interférence électromagnétique, de fiabilité des équipements ou de sécurité.
Le second type de signal utilisé par les radars UWB est l'*alternance sinusoïdale unique*, appelée aussi *impulsion monocycle*, de durée τ inférieure à 1 ns (Fig. 1d). Cette impulsion, qui a d'elle-même une valeur moyenne nulle, a un spectre formé de différents lobes dont le premier, qui est aussi le plus large, est centré sur la fréquence de la sinusoïde. Par rapport à l'impulsion unipolaire en bande de base, l'impulsion monocycle offre l'avantage d'avoir une densité spectrale qui n'est pas maximale à 0 Hz mais bien à une fréquence $F = 1/\tau$. Ainsi une impulsion de 1 ns aura son maximum de densité spectrale centré sur 1 GHz et 90 % de la puissance sera comprise entre 600 MHz et 1350 MHz., ce qui donne une largeur de bande relative de 75%. De même que pour l'impulsion en bande de base, l'impulsion monocycle est parfois codée pour accroître le facteur de charge (Fig. 1e).
Le troisième type de signal, appelé *impulsion polycycle*, est formé d'un nombre N déterminé de cycles d'une sinusoïde (Fig. 1f). Il s'agit là en fait d'une impulsion avec porteuse mais dont le nombre de cycles est beaucoup plus petit que dans l'impulsion de 1 us émise par un radar classique qui contient environ un millier de cycles. En réduisant à 5 ns la durée d'une sinusoïde de 1 GHz, le signal ne comporte plus que 5 cycles, ce qui porte sa largeur de bande relative à 20%. Les spectres d'amplitude d'impulsions polycycles de diverses longueurs ainsi que ceux des autres signaux à bande ultra-large sont représentés à la Fig.2

5. EMETTEURS POUR RADARS UWB

La durée du signal émis par un radar UWB étant extrêmement brève (< 1 ns), une puissance de crête très élevée est nécessaire pour atteindre la portée voulue. La portée d'un radar est en effet proportionnelle à l'énergie contenue dans l'impulsion rayonnée. Pour que l'énergie de l'impulsion mille fois plus courte soit la même que celle d'un radar classique, il faut que la puissance de crête soit augmentée dans le même rapport. Outre le fait que le signal est beaucoup plus bref et beaucoup plus puissant que pour un radar conventionnel, l'absence de fréquence porteuse fait que la plupart des émetteurs des radars usuels (magnétron, klystron, gyrotron, etc) ne peuvent être utilisisés tels quels. Il existe principalement deux techniques pour engendrer des impulsions de courte durée de forte puissance.

La première consiste à engendrer une impulsion de longue durée et de puissance modérée au moyen un émetteur classique et à comprimer la durée de l'impulsion, ce qui accroît aussi sa puissance de crête. Les recherches les plus avancées dans ce domaine se concentrent à l'Institut de Physique nucléaire de Tomsk, au Centre de l'Accélérateur linéaire de Stanford et au Lawrence Livermore National Laboratory. En accumulant l'énergie d'une impulsion de 3,6 us/1,6 MW fournie par un klystron en bande S dans un résonateur et en couplant ensuite brusquement celui-ci à une charge, l'équipe de Tomsk a obtenu une impulsion de 70 MW crête avec une durée comprise entre 15 et 50 ns, ce qui représente un facteur d'amplification de 40 et un taux de compression moyen de 200 [3]. Suivant le même procédé, une impulsion de 11 ns/350 MW a pu être engendrée à partir de l'impulsion de 550 ns fournie par un vircator [4].

La seconde technique consiste à utiliser une source qui s'apparente au générateur d'impulsions inventé par Hertz, dans lequel une capacité préalablement chargée à haute tension est brutalement déchargée à travers un commutateur de faible inductance. De tels systèmes sont employés depuis de nombreuses années mais à des niveaux de puissance inférieurs au MW. C'est la difficulté de produire des impulsions stables de plusieurs GW qui fut longtemps l'une des principales limitations à l'emploi des radars UWB. Ces dix dernières années cependant, de notables améliorations ont été apportées à la conception des commutateurs classiques tels que les éclateurs déclenchés et les transistors à avalanche pour augmenter leur puissance et leur rapidité. Par ailleurs, de nouveaux commutateurs à semi-conducteurs utilisant l'effet photoconducteur rapide induit par laser, ont vu le jour. Ces nouveaux commutateurs se profilent comme d'excellentes sources pour les radars UWB. Associés à de courtes lignes de

transmission de longueurs appropriées, ils permettent en effet de synthétiser une impulsion isolée ou un train d'impulsions de forme donnée avec un niveau de puissance considérable et une grande stabilité de phase. Les mérites respectifs des différents types de commutateurs utilisables dans les émetteurs à générateur hertzien sont examinés ci-après.

5.1 Commutateurs à éclateurs

L'utilisation d'*éclateurs déclenchés* pour commuter des tensions élevées est ancienne mais leur technologie n'a cessé de progresser. Les éclateurs à air permettent de commuter plusieurs dizaines de kilovolts et les éclateurs à gaz pressurisés ou à bain d'huile peuvent atteindre le mégavolt. La durée de commutation est de quelques nanosecondes pour les éclateurs ordinaires mais descend sous la nanoseconde avec les éclateurs les plus rapides dans lesquels l'arc électrique est initié par stimulation photonique[5]. Ainsi l'ETCA d'Arcueil a réalisé pour ses besoins propres[6] des générateurs utilisant ce type de stimulation. Parmi les générateurs disponibles sur le marché, le plus rapide est le générateur IKOR fabriqué par Omniwave[7], qui produit une impulsion de 1 kV/350 ps à la cadence de 250 Hz. De manière générale, la gigue des éclateurs est assez élevée, ce qui rend leur utilisation délicate et nécessite un traitement de signal particulier dans le récepteur radar pour pouvoir moyenner correctement le signal reçu sur plusieurs périodes et en améliorer le rapport signal-à-bruit. Les générateurs à éclateurs sont robustes, fiables et capables d'engendrer des puissances de crête de l'ordre du GW. Ils présentent l'inconvénient d'avoir une durée de vie limitée à cause de la dégradation des électrodes par l'arc électrique. Par ailleurs leur fréquence de répétition est limitée à quelques centaines de Hz.

Une alternative intéressante à l'éclateur à gaz, qui est du reste utilisée dans certains radars UWB, est le *thyratron à hydrogène*. Bien qu'il produise une moindre puissance, il fonctionne à des fréquences de répétition supérieures et sa gigue plus faible le rend utilisable pour alimenter une antenne réseau. Cependant, le temps de montée obtenu avec ces sources est trop long pour les applications à haute résolution radiale. Dans ce dernier cas, on peut cependant associer au thyratron une ou plusieurs lignes de compression d'impulsion. Il s'agit de lignes de transmission chargées de matériaux non linéaires à base de ferrites. Les lignes actuelles peuvent ramener un temps de montée de 2 ns à 100 ps environ pour des tensions de 10 kV. Des progrès sont néanmoins encore nécessaires pour réduire les pertes subies dans ces lignes ce qui permettrait de les employer à des fréquences de répétition plus élevées sans que la dissipation de chaleur ne devienne rédhibitoire.

5.2 Commutateurs à état solide

Les progrès incessants accomplis dans l'industrie des semi-conducteurs ont permis la réalisation de générateurs à état solide capables d'engendrer des impulsions ultra-brèves (de 100 ps à 1 ps) à des puissances de crête non négligeables. On peut ranger ces sources en deux catégories suivant leur mode de déclenchement qui est électronique ou bien optique. Dans la première catégorie figurent les générateurs à transistors à avalanche et à diode de redressement (Step Recovery Diode) et dans la seconde les générateurs qui utilisent l'effet photoconducteur rapide commandé par impulsion laser.

Le *transistor à avalanche* convient bien à la création de signaux de puissance à front de montée très raide. Bien que la tension de disruption d'un transistor isolé soit relativement faible (quelques centaines de volts), il est possible d'obtenir par mise en série un coefficient de mérite de 1 à 10 kV/ns. Ainsi le générateur de Irco fournit un échelon de 1 ns de temps de montée à un niveau de 10 kV avec une fréquence de répétition de 1 kHz et une gigue de 200 ps. Le générateur SPSV de Kentech fournit quant à lui une impulsion de forme gaussienne de 2 kV avec une durée à mi-hauteur de 200 ps et une gigue de 10 ps seulement. Dans certains générateurs, on utilise le transistor à avalanche conjointement avec une ou plusieurs SRD (*Step Recovery Diode*). Le temps de montée très court de ces diodes mises en cascade permet de redresser le front de montée plus lent du transistor et d'obtenir des temps de montée de 100 ps.

Ces dernières années de sérieux progrès ont été accomplis dans la miniaturisation des générateurs à état solide de forte puissance. A ce propos on peut citer les sources BASS (*Bulk Avalanche Semiconductor Switch*) développées récemment par la firme Pulse Power Physics [8]. Ces générateurs entièrement connectorisés et très compacts (vol < 20 cm3) fournissent une puissance de crête de 500 kW (5kV dans 50 Ohms) avec un temps de montée de 120 ps et une fréquence de répétition de 1 kHz, la gigue n'étant que de 20 ps. Fabriquées à partir de composants électroniques commerciaux, ces sources alimentées en 28 Vdc sont d'un prix tout à fait abordable et d'une bonne fiabilité (durée de vie >108 impulsions).

La seconde catégorie de sources à l'état solide est constituée par les commutateurs à déclenchement optique. Un important travail de recherche s'effectue actuellement tant en Europe qu'aux Etats-Unis pour tenter de convertir des impulsions optiques extrêmement courtes (<10 ps) en impulsions électriques par effet photoconducteur rapide dans les semi-conducteurs massifs (effet Auston, 1975). Depuis sa découverte sur le silicium, cet effet a été observé dans d'autres matériaux (Cr:GaAs, GaAs, Fe:InP, Ge, GaP et diamant) et des commutateurs expérimentaux ont été mis au point. Auston lui-même a produit aux Bell Laboratories des impulsions de 10ps/100V et Antonetti rapporte la production d'une impulsion de 50 ps/10 kV avec une gigue quasi nulle[9]. Cette dernière qualité fait des commutateurs à déclenchement optique des sources idéales pour alimenter les différents éléments rayonnants d'une antenne à réseau phasé. La Fig. 3 montre que l'élément actif du commutateur est constitué par un petit barreau de semi-conducteur (2 à 5 mm de long et 1 mm2 de section) inséré dans un court tronçon de ligne coaxiale ou microruban à large bande. La création de porteurs induits dans le barreau par une illumination laser d'énergie photonique égale à la largeur de bande interdite du semi-conducteur a pour effet d'accroître suffisamment sa conductivité pour que son impédance deviennent brutalement inférieure à celle du tronçon de ligne et rende celui-ci passant. Le temps de montée de l'impulsion électrique qui peut ainsi être transféré de la capacité de stockage à la charge (antenne) dépend de la durée de l'impulsion optique et de la bande passante de la ligne dans laquelle est placé l'élément actif.

G. Mourou de l'Ultra-fast Science Laboratory à l'université du Michigan à réussi à commuter 1 kV en 1 ps avec une gigue de 2 ps [10]. Par ailleurs, Thomson Short Systems a récemment mis sur le marché ce que l'on peut considérer comme l'un des premiers générateurs d'impulsions de puissance à photoconductivité laser, l'illumination se faisant au moyen d'un laser Nd:Yag. L'impulsion électrique obtenue est un signal rectangulaire de 30 kV/10 ns avec un temps de montée de 200 ps, une gigue de 10 ps et une fréquence de répétition de 100 Hz [11]. Les Sandia National Laboratories quant à eux ont développé un commutateur du même type [12] : une ligne de 50 Ohms portée à la tension de 100 kV se décharge à travers un commutateur activé par une impulsion optique de 90 nJ. L'impulsion électrique engendrée a une puissance de crête de 48 MW, un temps de montée de 430 ps et une durée totale de 1,4 ns [13]. Enfin, la firme ECR (Energy Compression Research) a pu engendrer une impulsion de 32 ps/118 MW au moyen de jonctions au silicium montées sur des lignes de transmission TEM à très basse impédance (<1 Ohm), épaisses

de 50 um seulement, la jonction étant activée par une impulsion laser de 35 ps. En variant la configuration des lignes, en combinant celles-ci en série ou en parallèle et en les activant soit en synchronisme, soit de façon séquentielle, des impulsions de forme diverses (monocycle, gaussienne, sinus amorti) ont pu être engendrées à des puissances de crête de 100 MW et avec des temps caractéristiques inférieurs à 100 ps [14]. Des essais de durée de vie indiquent que ces commutateurs sont d'une grande fiabilité : après deux millions de commutations à 60 MW à la fréquence de répétition de 10 Hz, aucune défaillance n'a été constatée.

6. ANTENNES POUR RADARS UWB

Les radars classiques à bande étroite utilisent principalement l'antenne à réflecteur parabolique et l'antenne planaire en réseau phasé. Ces antennes directives sont conçues pour présenter un gain important à la fréquence porteuse avec un faible niveau de lobes secondaires, le balayage étant réalisé soit de manière mécanique, soit de manière électronique. Ces antennes ont malheureusement une bande passante bien trop étroite pour être adaptées aux besoins des radars UWB qui nécessitent une antenne apte à fonctionner en régime transitoire et à rayonner sans distorsion le signal non sinusoïdal ou impulsionnel appliqué à ses bornes. L'antenne d'émission d'un radar UWB doit par conséquent avoir un *gain le plus constant possible* sur une très large bande de fréquence (BW>0,25) pour éviter la distorsion d'amplitude, mais doit aussi présenter une *grande linéarité de phase* sur la même étendue spectrale pour limiter la distorsion de phase. Cette dernière qualité, qui n'est pas requise pour un radar à bande étroite, est en revanche essentielle pour l'antenne d'un radar UWB qui tire précisément toute l'information sur la nature de la cible de la forme temporelle de l'écho. Naturellement, l'antenne doit aussi présenter une bonne *directivité* pour conférer au radar la résolution angulaire nécessaire. Il est souhaitable également que la *polarisation* de l'antenne soit contrôlée sur toute la largeur spectrale de l'impulsion rayonnée, afin de pouvoir enregistrer la réponse de la cible dans les diverses polarisations (hh,vv,hv,vh). Enfin, pour que l'antenne puisse fonctionner à une *puissance de crête* de l'ordre du GW, un traitement particulier est nécessaire au niveau du point d'alimentation : les faibles dimensions physiques en ce point et la tension très élevée qui y règne peuvent en effet poser des problèmes de claquage dans l'air. La solution adoptée généralement consiste à placer la zone proche du point d'alimentation dans un bain d'huile ou dans un coffret pressurisé rempli d'hexaflourure de soufre, gaz dont la tension de claquage est supérieure à celle de l'air.

Deux approches sont utilisées dans la conception d'une antenne pour radar UWB.

La première consiste à utiliser une antenne <u>dispersive</u> telle que *l'antenne log-périodique* pour engendrer une impulsion rayonnée de plus courte durée que l'impulsion électrique appliquée à ses bornes [15],[16]. La difficulté avec ce type d'antenne qui effectue en fait une compression d'impulsion est de réaliser une mise en forme adéquate du signal appliqué aux bornes de l'antenne pour que l'impulsion rayonnée ait la forme temporelle désirée.

La seconde approche consiste à utiliser une antenne <u>non dispersive</u> à bande ultra-large capable de transmettre l'impulsion sans distorsion. Parmi les diverses formes d'antenne à avoir été étudiées figure le *cornet TEM* [17],[18],[19]. Contrairement aux cornets électromagnétiques usuels, le cornet TEM n'a pas de parois métalliques latérales : il est constitué de deux conducteurs métalliques en forme de plaques triangulaires faisant un angle β entre elles (Fig. 4), ce qui lui permet de véhiculer le mode TEM, mode pour lequel la vitesse de propagation de l'onde est indépendante de la fréquence. C'est cette propriété qui confère au cornet TEM sa grande bande passante. Dans les cornets usuels, qui sont en fait des guides d'ondes évasés à leur extrémité, la vitesse de l'onde dépend de la fréquence de sorte que le temps de transit de l'onde de l'apex à l'ouverture rayonnante dépend de la fréquence (effet dispersif). Par ailleurs, la bande passante d'un cornet usuel, limitée par l'apparition du mode d'ordre supérieur dans le guide, ne dépasse pas un rapport de 1,8:1. Le cornet TEM en revanche offre une bande passante qui peut atteindre un rapport de 10:1.

De manière simplifiée, on peut se représenter un bon modèle à basse fréquence du cornet TEM comme une ligne de transmission conique en circuit ouvert. Ce modèle revient à considérer la ligne comme la mise en cascade d'éléments de ligne infinitésimaux. Le courant et la charge étant connus sur chacun de ces segments en fonction du temps, on peut les représenter comme une cascade de dipôles électriques et magnétiques répartis. En sommant les champs rayonnés par tous ces dipôles, on obtient une bonne approximation du champ engendré par les basses fréquences contenues dans l'impulsion, c.-à-d. du rayonnement transitoire à long terme, lequel est directement proportionnel à la tension d'excitation. Quant au rayonnement transitoire à court terme, qui correspond aux hautes fréquences de l'impulsion, il peut être évalué par la théorie géométrique de la diffraction. En effet, lorsqu'un échelon de tension est appliqué à l'apex du cornet, la différence de potentiel appliquée entre ses plaques engendre une onde sphérique TEM qui progresse jusqu'à la section terminale où elle est diffractée. Lorsque les dimensions transverses du cornet restent faibles devant la plus petite longueur d'onde présente dans l'excitation, l'impulsion rayonnée dans l'axe aux premiers instants est proportionnelle à l'impulsion excitatrice. Par contre, si les dimensions transverses du cornet sont grande par rapport à la longueur d'onde, le rayonnement à court terme est proportionnel à la dérivée première de la tension excitatrice. Le rayonnement latéral du cornet, c.-à-d. dans des directions qui s'écartent de l'axe de symétrie, est caractérisé par une dégradation du temps de montée et un élargissement de l'impulsion. La raison en est que l'angle d'ouverture du lobe principal d'une antenne est inversement proportionnel à la fréquence. L'intensité du rayonnement décroît donc plus rapidement avec l'angle θ pour les hautes fréquences que pour les basses fréquences, et donc l'impulsion rayonnée devient de plus en plus longue au fur et à mesure que l'on s'écarte de l'axe. Par suite, il faut toujours veiller à ce que l'antenne cornet soit correctement pointée vers son objectif. Il y a différentes façons d'alimenter le cornet TEM par la source impulsionnelle. Le plus commode est d'utiliser un câble coaxial fixé à la gorge du cornet de telle façon que le conducteur extérieur soit soudé à la plaque inférieure et que le conducteur intérieur, prolongé, vienne en contact avec la plaque supérieure. Le couplage entre le câble coaxial, qui véhicule déjà le mode TEM, et l'antenne qui fonctionne suivant le même mode, est ainsi optimal.

A la réception, un cornet TEM électriquement grand engendre à ses bornes une impulsion de tension qui est directement proportionnelle à l'impulsion de champ incident. Ceci est dû au fait que la fonction de transfert à la réception - définie comme le rapport de la transformée de Fourier de la force électromotrice induite à la transformée du champ électrique incident - devient constante à haute fréquence. En vertu du théorème de Carson-Lorentz dans sa formulation temporelle, on sait en effet que la réponse impulsionnelle d'une antenne à la réception est proportionnelle à l'intégrale de sa réponse impulsionnelle à l'émission.

Diverses améliorations peuvent être apportées au cornet TEM. La réflexion subie par l'onde progressive de courant à l'extrémité des plaques peut être réduite en chargeant le cornet résistivement : au lieu d'utiliser du métal sur toute la longueur des plaques, la section terminale est réalisée en un matériau résistif qui tend à absorber le courant avant qu'il n'atteigne le bord. La puissance rayonnée par le cornet en est un peu diminuée mais sa largeur de bande est nettement améliorée du fait du meilleur taux d'onde stationnaire ainsi obtenu. Une autre

amélioration consiste à ajouter au cornet une lentille diélectrique de focalisation pour compenser la sphéricité du front d'onde excitant l'ouverture rayonnante. Le décalage temporel avec lequel les différents points de l'ouverture plane sont atteints par l'onde sphérique tend en effet à avachir l'impulsion rayonnée. En plaçant entre les deux plaques une lentille diélectrique à profil d'indice judicieusement calculé, le temps de transit de l'onde de l'apex à chaque point de l'ouverture plane est rendu constant, ce qui permet de préserver le temps de montée et la durée de l'impulsion fournie par la source.

Une autre antenne conçue pour rayonner des impulsions ultra-brèves à de grandes distances est l'antenne dénommée *IRA (Impulse Radiating Antenna)* [20],[21],[22],[23]. C'est une antenne à réflecteur parabolique dont la source primaire n'est pas un cornet électromagnétique usuel mais une ligne de transmission TEM de forme conique (Fig.5). Une des principales limitations de la bande passante d'une antenne parabolique classique est en effet que le cornet illuminant le réflecteur ne fonctionne correctement que sur un peu moins d'une octave. Au-delà de l'octave, le diagramme de rayonnement est altéré par l'apparition des modes d'ordre supérieur dans le cornet. L'utilisation de la ligne conique permet d'illuminer le réflecteur avec une onde sphérique TEM. Celle-ci prend naissance à l'apex de la ligne placé au foyer de la parabole et atteint le réflecteur qui la focalise dans l'axe de la parabole. Le mode TEM n'ayant pas de fréquence de coupure, la bande passante n'est plus limitée par la source primaire. De manière simplifiée on peut expliquer le rayonnement de l'antenne IRA comme suit : supposons qu'un échelon de tension de temps de montée égal à τ soit appliqué à l'apex de la ligne conique; un observateur situé à grande distance sur l'axe de symétrie de la parabole voit d'abord arriver une pré-impulsion de durée égale à 2F/c où F est la distance focale du réflecteur et c la vitesse de la lumière dans le vide. Cette pré-impulsion, qui a la même forme d'échelon que la tension appliquée, est due au rayonnement direct du courant lancé sur la ligne de transmission conique. Elle est suivie d'une impulsion de grande amplitude et de durée τ qui correspond en fait à la dérivée première de l'échelon appliqué : c'est la contribution du réflecteur parabolique. Enfin, l'impulsion principale est suivie d'une "queue" de faible amplitude associée aux basses fréquences du signal et qui est due à la réflexion du courant au bout de la ligne de transmission conique. Pour limiter l'importance de cette réflexion qui contribue ausssi à augmenter le taux d'onde stationnaire de l'antenne et donc à limiter sa bande passante -, des résistances sont insérées entre le bout de la ligne et le plan réflecteur pour absorber le courant avant qu'il ne parvienne au réflecteur. La limite basse fréquence de la bande passante de l'antenne IRA est fixée par son diamètre.

A défaut de pouvoir réaliser une antenne unique qui soit à la fois directive et à bande ultra-large, certains se sont tournés vers le concept de *réseau d'antennes*. Il est bien connu en effet qu'en combinant les rayonnements d'un grand nombre de sources peu directives, voire même isotropes, on peut obtenir un effet de directivité très prononcé. Comme il n'est pas trop difficile de réaliser une source à bande ultra-large qui soit isotrope ou en tous cas omnidirectionnelle (en utilisant par exemple de petites antennes dipôles chargées résistivement ou des antennes biconiques), on peut chercher à renforcer la directivité d'une collection de telles sources dans des directions déterminées en les disposant en réseau. Le problème est cependant ici plus complexe qu'avec un réseau de sources monochromatiques car les directions d'interférences constructives ne sont pas les mêmes pour toutes les fréquences contenues dans l'impulsions rayonnée. Si plusieurs travaux théoriques importants ont déjà été faits dans ce domaine [24],[25],[26],[27], beaucoup reste à faire. Outre la directivité accrue, le réseau d'antennes offre également la possibilité du balayage électronique de faisceau. Dans le cas d'un réseau à bande ultra-large rayonnant des impulsions extrêmement brèves, les sources qui alimentent les éléments du réseau doivent impérativement présenter une gigue de phase très faible. Les générateurs à base de commutateurs à effet photoconducteur rapide semblent particulièrement indiqués pour ce genre d'antenne.

7. RECEPTEURS POUR RADARS UWB

Dans le récepteur superhétérodyne d'un radar classique le signal reçu est amplifié et mélangé au signal fourni par l'oscillateur local qui le convertit en un signal à fréquence intermédiaire (IF). Après une deuxième amplification, le signal à porteuse IF subit une détection d'enveloppe (ou un filtrage adapté) avant d'être appliqué à l'amplificateur video et puis à l'unité de visualisation. La détection se produit lorsque l'amplitude du signal IF redressé (ou la sortie du filtre adapté) dépasse un seuil déterminé. Cette structure n'est évidemment pas utilisable dans un radar UWB pour la simple raison que le signal reçu ne contient pas de porteuse. Du point de vue fonctionnel, la structure d'un récepteur UWB doit être telle qu'il puisse non seulement décider de la présence ou non d'un signal utile lié à la cible - c'est la fonction *détection* -, d'en déterminer la position - c'est la fonction *localisation* -, mais aussi d'en faire la *reconnaissance*, voire l'*identification*. Pour cette dernière fonction, le récepteur UWB a besoin d'un rapport signal-à-bruit suffisamment élevé pour que les fins détails contenus dans la forme temporelle du signal observé et représentatifs de l'objet, ne soient pas noyés dans le bruit. En effet, alors que dans un récepteur classique, seule la puissance du signal (éventuellement son décalage Doppler) ont de l'importance, dans un radar UWB, la forme temporelle du signal reçu doit aussi être préservée. Le récepteur doit pouvoir restituer les fronts de montée et de descente très raides du signal sans distorsion : sa bande passante doit donc être ultra-large et la détection doit se faire en amont de tout élément dissipatif qui pourrait déformer l'impulsion à analyser. Comme la puissance de bruit collectée par le récepteur est proportionnelle à sa bande passante, on comprend tout l'intérêt qu'il y a à pourvoir le radar UWB d'un émetteur particulièrement puissant. Ce point pose d'ailleurs un problème technologique difficile : celui de la protection du récepteur pendant l'émission de l'impulsion (de plusieurs GW) par l'émetteur. Comme il est actuellement difficile de réaliser des commutateurs de puissance suffisamment rapides, on utilise dans la plupart des cas des antennes séparées pour l'émission et la réception. Mais même dans ce cas, l'isolation peut être insuffisante surtout lorsqu'il y a des structures métalliques résonantes dans le voisinage des antennes.

Sur le plan des performances, un radar UWB peut être caractérisé par une portée de détection et par une portée de reconnaissance, toujours inférieure à la première. Ces portées dépendent pour une grande part des mêmes paramètres que pour un radar classique, à savoir la puissance de l'émetteur, les gains d'antenne, la surface équivalente radar de la cible, la puissance de bruit à l'entrée du récepteur et le rapport signal-à-bruit minimal nécessaire compte tenu des probabilités de détection et de fausse alarme imposées. Mais elles dépendent aussi des caractéristiques statistiques du bruit et des interférences possibles avec d'autres émetteurs à bande étroite qui tombent dans la très large bandepassante du récepteur. En fait, l'hypothèse de bruit blanc additif gaussien est rarement satisfaite pour un radar UWB, étant donné son étendue spectrale et l'on doit plutôt considérer que le bruit est coloré.

On distingue principalement deux types de récepteurs UWB [28]: le récepteur à *détection de seuil* et le récepteur à *corrélation*. Dans les deux types de récepteur, le signal reçu est directement appliqué au détecteur sans subir de transformation de fréquence.

La détection de seuil requiert que l'amplitude du signal dépasse un seuil déterminé qui est généralement un multiple du niveau

de bruit propre du récepteur. Le détecteur de seuil proprement dit utilise soit des éléments linéaires soit des éléments non linéaires tels que des diodes à effet tunnel pour détecter la présence de l'impulsion UWB et la convertit en un signal de plus longue durée qui est alors appliqué à l'unité de traitement et de visualisation (Fig. 6).
Dans le récepteur à corrélation, le signal reçu est comparé à un signal temporel de référence, et la sortie du comparateur, qui est proportionnelle à leur degré de ressemblance, est appliquée à l'unité de traitement et de visualisation (Fig. 7). La détection se produit lorsque la correspondance entre les deux signaux dépasse un degré préétabli.

8. TRAITEMENTS DE SIGNAL POUR RADARS UWB

Le caractère non stationnaire des signaux transitoires, leur grande largeur spectrale et le fait que l'information recherchée sur la cible réside dans la forme temporelle de l'écho font que la plupart des techniques d'analyse mises en oeuvre dans les récepteurs classiques à bande étroite ne conviennent pas aux récepteurs UWB. La recherche de traitements spécifiques étant en pleine évolution, l'énumération faite ci-après ne doit pas être regardée comme exhaustive, mais seulement comme indicative des lignes de force qui se dégagent des travaux récents accomplis dans ce domaine.

8.1 Insuffisance de la transformation de Fourier

La transformée de Fourier, qui joue un rôle capital dans l'analyse des systèmes linéaires invariants dans le temps, attribue à un signal un ensemble de coefficients qui donnent l'amplitude et la phase relative des fonctions de base harmoniques (sinus et cosinus) en lesquelles le signal est décomposé. Comme les fonctions sinus et cosinus sont des fonctions de durée infinie, elles ne sont pas les plus indiquées pour restituer la forme d'un signal à support temporel borné tel qu'une impulsion. Il semble plus naturel en effet de décomposer un signal de durée finie en une somme pondérée de fonctions de base de durée finie plutôt que de durée infinie. Par ailleurs, aussi riche soit l'analyse de Fourier, elle se limite au seul plan fréquentiel et la localisation temporelle d'un événement perturbateur modifiant la valeur du signal à un instant précis se révèle difficile; cette information est même irrémédiablement perdue dans le spectre d'amplitude. En outre, si le signal est non stationnaire, les valeurs des coefficients de Fourier varient dans le temps.

8.2 Transformation de Fourier à court terme (TFCT)

C'est le physicien Gabor qui proposa dans les années quarante la première transformation temps-fréquence, baptisée *transformation de Gabor*. Cette transformation à fenêtre (gaussienne) glissante est en fait un cas particulier de ce que l'on nomme aujourd'hui la *transformation de Fourier à court terme* (Short Term Fourier Transform) [29],[30]. Au lieu de calculer la transformée de Fourier du signal à analyser, on calcule la transformée du signal préalablement multiplié par une fenêtre temporelle de forme déterminée, centrée sur un instant to donné et modulant l'amplitude de la fréquence F à laquelle la transformée est calculée. En faisant glisser l'instant to sur l'axe des temps, on calcule en fait la transformée de Fourier sur des tranches successives du signal. On obtient ainsi une représentation en trois dimensions avec la valeur de la transformée de la grandeur physique en axe vertical (Z) et les axes temps (X) et fréquence (Y) dans le plan horizontal (Fig. 8). La projection orthogonale de la surface tridimensionnelle dans le plan horizontal fournit la représentation temps-fréquence du signal. Une telle représentation permet notamment de mettre en évidence des phénomènes dispersifs et aussi d'identifier les fréquences de résonance présentes dans le signal et leurs instants d'occurence. Les résolutions temporelle et fréquentielle de cette représentation sont uniformes dans tout le plan et sont liées par le principe d'incertitude de Gabor : plus la fenêtre temporelle utilisée est de courte durée, meilleure est la résolution dans le temps mais moins bonne est la résolution fréquentielle. Inversement, on peut améliorer la résolution fréquentielle en choisissant une fenêtre temporelle plus longue. Gabor a montré que le meilleur compromis entre localisation temporelle et résolution fréquentielle est obtenu avec la fenêtre gaussienne.

8.3 Transformation en ondelettes (TO)

L'analyse en ondelettes propose une évolution importante de la TFCT en ce sens qu'elle adopte une fenêtre de durée variable en fonction de la zone spectrale à analyser, de manière à maintenir constante la résolution fréquentielle <u>relative</u>. Ceci est réalisé en combinant le décalage temporel de la fenêtre (comme dans la TFCT) à une contraction ou dilatation d'échelle (au lieu d'une modulation pour la TFCT). En effet, si l'on peut se satisfaire d'une résolution de 1 kHz au voisinage d'une fréquence de 1 MHz, cette résolution devient insuffisante au voisinage d'une fréquence de 100 Hz, où la résolution devrait passer à 0,1 Hz pour conserver la même finesse d'analyse. La transformation en ondelettes réalise en fait une analyse de type multirésolution [31],[32],[33].

8.4 Méthode d'expansion des singularités (SEM)

La méthode SEM (Singularity Expension Method) consiste à modéliser un signal transitoire par un ensemble de points singuliers dans le plan complexe qui correspondent à des résonances et à des amortissements caractéristiques de l'objet. Cette représentation du signal sous la forme d'une somme pondérée de sinusoïdes amorties offre l'avantage d'être plus compacte en ce sens que le signal est décrit par un plus petit nombre de coefficients (les pôles de la fonction de transfert et leurs résidus) qu'avec la transformée de Fourier. Une cible excitée par un signal impulsionnel tend naturellement à annuler sa réponse après un certain temps. Des mesures effectuées sur diverses formes de cible en vrai grandeur et sur modèle réduit indiquent que la réponse impulsionnelle d'une cible comporte grosso modo deux parties : une réponse à court terme et une réponse à long terme. La première est caractérisée par des pics assez intenses et de très courte durée dont l'amplitude dépend fortement de la forme de la cible et de son orientation par rapport à l'onde incidente. Cette réponse à court terme, qui est en fait liée aux réflexions spéculaires sur la cible peut souvent être modélisée par une somme pondérée de doublets. La réponse à long terme de la cible, généralement moins intense et de plus longue durée, est moins dépendante de l'angle d'aspect et est liée aux résonances naturelles de la cible laissée à elle-même après que l'excitation ait pris fin. L'avantage de la décomposition de la réponse à long terme en pôles est que la position de ceux-ci dans le plan complexe est indépendante de l'angle d'aspect, seule la valeur des résidus étant affectée par un changement d'orientation de l'objet. En revanche, la méthode pêche par son manque de robustesse en présence de bruit additif. Comme la réponse à long terme est souvent de faible amplitude, le bruit limite la précision de la localisation des pôles [34],[35],[36].

8.5 Analyse spectrale d'ordre supérieur

L'estimation du spectre de puissance du signal est une méthode qui a été appliquée avec succès à de nombreux problèmes de reconnaissance et d'identification. Cependant l'estimation du spectre de puissance met surtout l'accent sur le contenu spectral mais supprime les relations de phase entre les composantes du signal. En d'autres termes, deux signaux peuvent avoir le même spectre de puissance mais deux formes temporelles différentes. Pour pouvoir les distinguer, il faut recourir à l'analyse spectrale d'ordre supérieur. Celle-ci permet en outre de s'affranchir des effets d'un bruit additif coloré - pour un radar UWB, le bruit peut rarement être considéré comme blanc - de distinguer des signaux à phase non minimale et de détecter la présence de non

linéarités dans le signal. L'une des techniques les plus utilisées est l'analyse bispectrale [37],[38].

9. CONCLUSION

L'objet de cet article était de donner un aperçu de l'état de l'art atteint dans la technologie des radars à bande ultra-large. Ces radars dont la technologie n'est pas encore mature, diffèrent des radars classiques par la forme temporelle des signaux émis, leur largeur spectrale instantanée (BW>0,25) et la puissance de crête. Ces caractéristiques particulières font que les émetteurs, les antennes et les récepteurs employés dans les radars usuels ne conviennent pas aux radars UWB ou, en tous cas, pas sans adaptations préalables.

Pour engendrer des impulsions de forme adéquate (monocycle, gaussienne, polycycle) de durée extrêmement brève (<1ns) à un niveau de puissance considérable (GW), deux solutions sont possibles. La première est d'utiliser l'impulsion avec porteuse fournie par un émetteur classique (impulsion de longue durée et de puissance modérée) et de la comprimer au moyen d'un résonateur couplé à un commutateur rapide. On peut obtenir par cette méthode des impulsions de type polycycle, voire monocycle. La deuxième solution est d'utiliser un générateur d'impulsion hertzien, constitué d'une source de haute tension, d'une capacité de stockage (la capacité d'un banc de condensateurs ou la capacité répartie d'une ligne de transmission) et d'un commutateur ultra-rapide par lequel la capacité de stockage est déchargée dans l'antenne d'émission. Les différents commutateurs utilisables (à déclenchement électronique ou optique) ont été discutés et leurs mérites respectifs comparés.

Les antennes requises pour les radars UWB doivent être à la fois directives et à bande ultra-large et pouvoir soutenir la puissance de crête considérable qui est nécessaire. Si certaines antennes dispersives à large bande telles que l'antenne log-périodique sont envisageables - c'est alors l'antenne elle-même qui réalise la compression de l'impulsion -, les antennes les plus adaptées sont des antennes non dispersives telles que le cornet TEM et l'antenne IRA. Ces antennes offrent en effet l'avantage de préserver la forme temporelle du signal et de présenter un gain non négligeable. Si ce gain est insuffisant pour l'application envisagée, les antennes peuvent alors être agencées en réseau et commandées par des générateurs à faible gigue tels que les commutateurs utilisant l'effet photoconducteur rapide induit par impulsion laser.

L'absence de porteuse dans le signal émis par un radar UWB rend inutilisable le récepteur superhétérodyne d'un radar classique à bande étroite. Deux structures de récepteur sans mélangeur sont généralement utilisées : le récepteur à détection de seuil et le récepteur à corrélation. Ces deux structures ont été brièvement décrites et commentées. Enfin, les techniques de traitement de signal spécifiques aux signaux transitoires à large bande ont été décrites et comparées.

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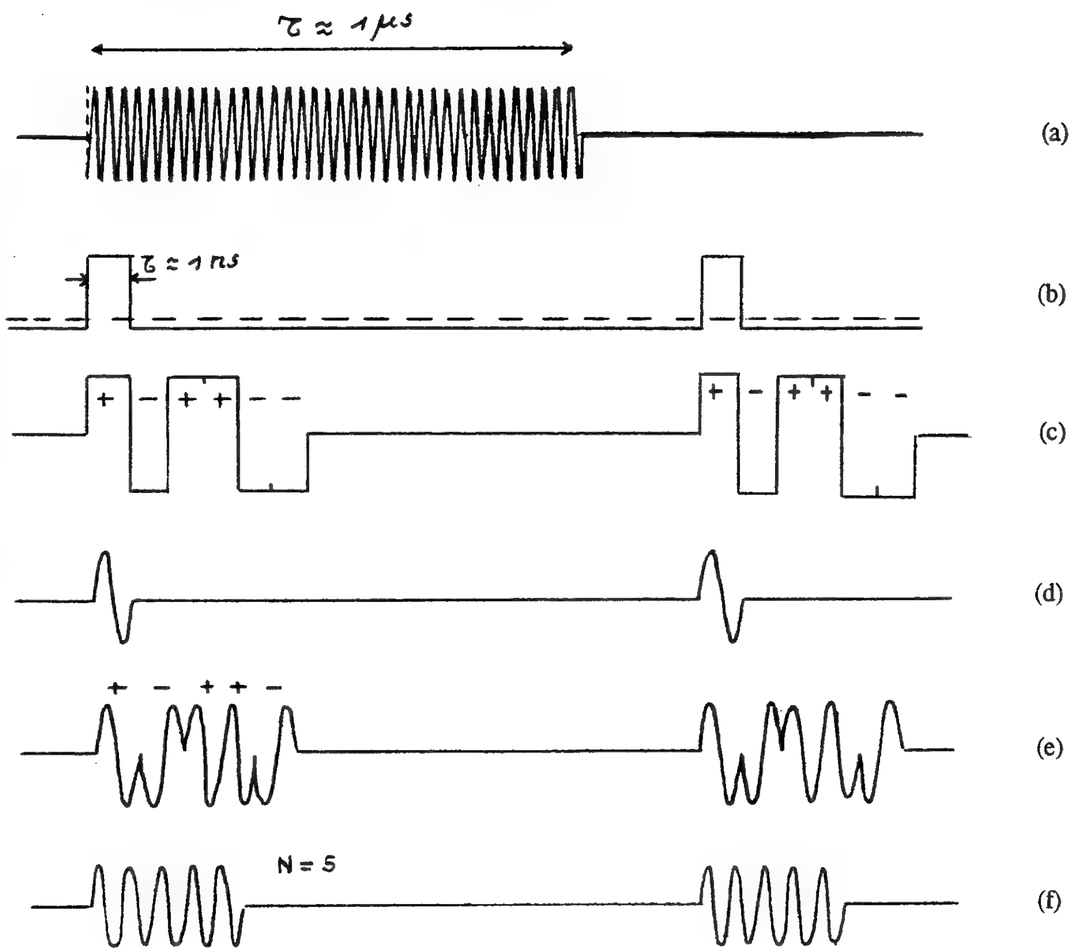

Fig. 1 Forme temporelle des signaux émis par un radar classique (a)
et par les radars à bande ultra large (b à f)

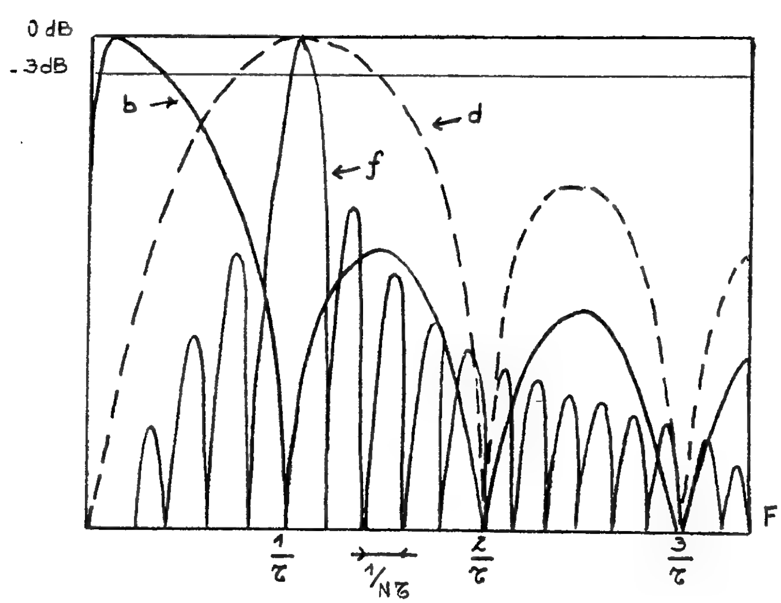

Fig. 2 Densité spectrale de puissance des signaux émis par les radars à bande ultra-large

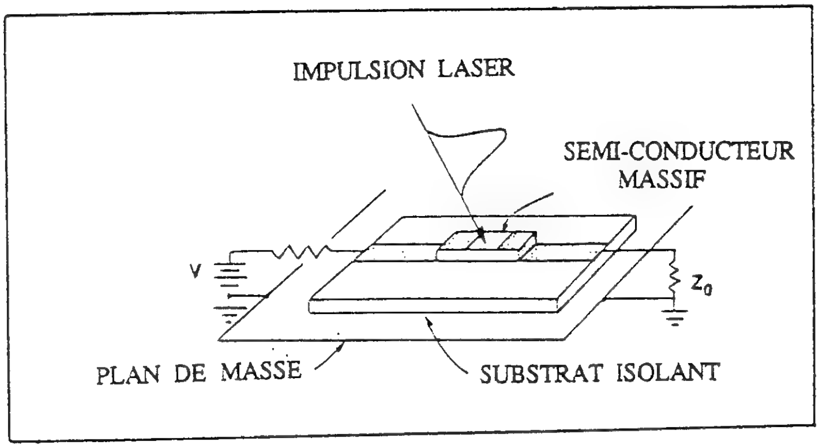

Fig. 3 Commutateur à effet photoconducteur rapide induit par laser

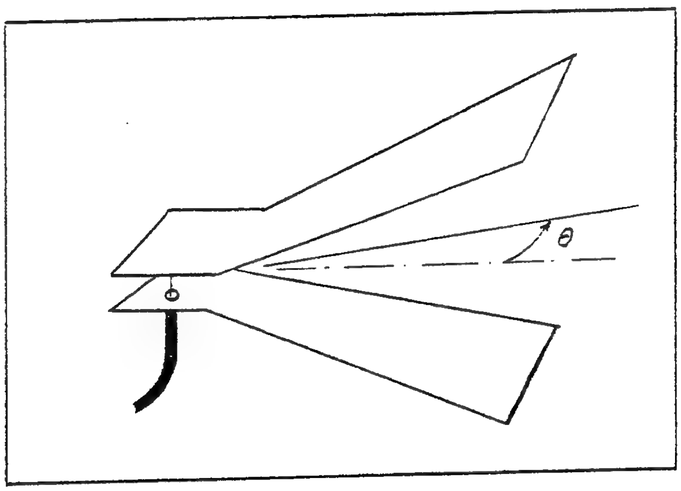

Fig. 4 Le cornet TEM

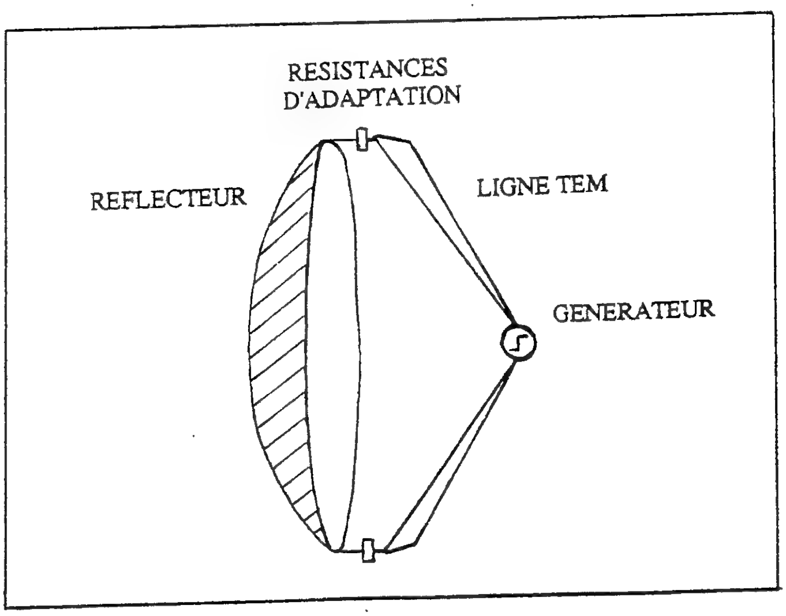

Fig. 5 L'antenne IRA

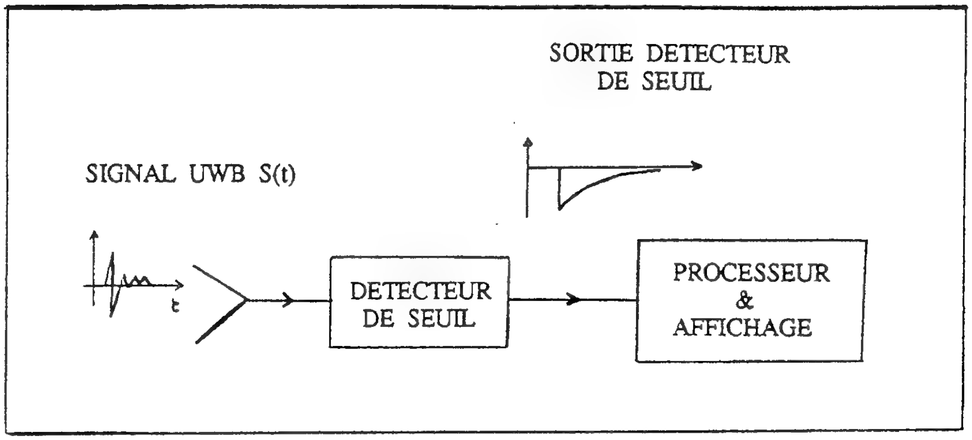

Fig. 6 Schéma fonctionnel d'un récepteur UWB à détection de seuil

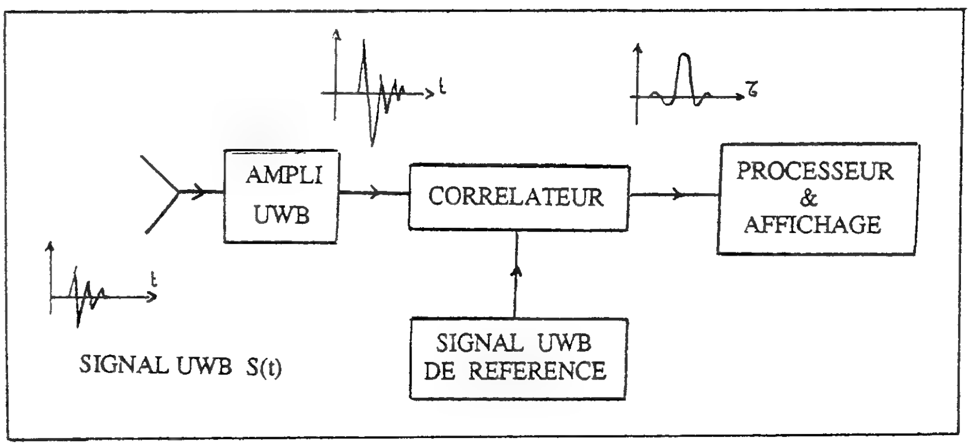

Fig. 7 Schéma fonctionnel d'un récepteur UWB à corrélation

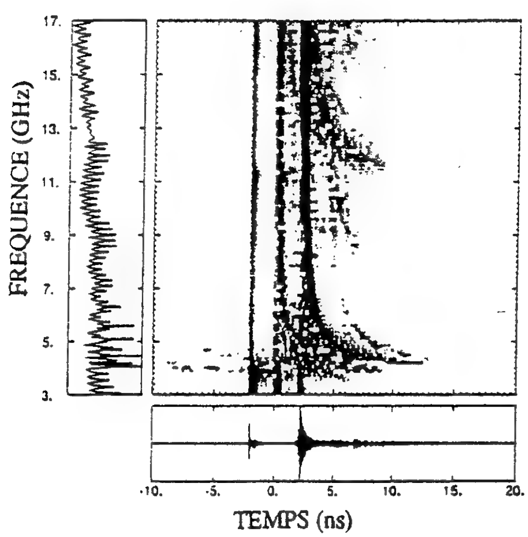

Fig. 8 Analyse temps-fréquence d'un signal non stationnaire

High-Power Microwaves Effects on Smart Electronic Weapon Systems

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Summary

In this paper we describe the coupling of microwaves to smart electronic weapon systems. Analytical and numerical calculations of an almost real model of a weapon system give a first idea concerning the results of a strong interaction of an electromagnetic wave with the system under consideration. Subsequent experiments with the *passive* system confirm the expected results and/or add new, sometimes unexpected ones to the former. They together form the basis for the final tests with the *active* smart system. Whereas the passive tests mainly are performed with low power excitation in the cw-modus, experiments with the active system are conducted with quite different power levels and the variation of many other HPM-parameters. The magnitudes of the perturbation quantities inside the system are measured and stored and serve as input data for a flightpath simulation program. With the aid of such a program one can make a prediction whether or not the smart weapon system can fulfill its mission. It is shown that interferences lasting longer than about 1.5 s lead to mission interruption. Hardening and defense aspects are discussed at the end of the paper.

1. Introduction

Recently, the potential for high-power microwaves (HPM) weapons has increased due to advances in source technology and the increased vulnerability of targets because of a widespread use of solid state electronics. Therefore the goals of national HPM programs are to develop weapon systems to defeat smart ammunition and thereby to protect military systems like, e.g., large airports and expensive warships against potential HPM threats. Moreover, these programs are complemented by survivability measurements, prediction of HPM effects on military systems and the development and demonstration of hardening measures for own systems.

The hierarchy of HPM directed energy effects ranges from burnout of or lethal damage to enemy electronic systems to the deception or spoofing of the enemy system into mission failure. This last mission is very akin to electronic warfare (EW) at higher power levels, and therefore broader classes of targets can be attacked, in distinction to EW techniques which are very target-specific.

The distinction between HPM directed energy and EW can be seen in terms of a trade-off between the power level and the sophistication of the attack. EW uses sophisticated techniques at much lower power to deny any opponent effective use of communications and control and has become expensive due to the threat diversity and the electronic countermeasure / electronic counter-counter-measure competition.

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HPM can access new generic effects and lead to less threat-specific attacks. An intermediate region has developed in which features of both HPM and EW are combined known as *smart rf directed energy*. These techniques use repetitive microwave pulse formats with amplitude and frequency modulation and pulse shape control.

Since it is not easy to calculate, *a priori*, the effectiveness of HPM weapons, simulation testing is required to evaluate the sensitivity of military hardware and systems, and to determine methods for hardening friendly systems against HPM threats. As a result, HPM simulators must be designed and built for use in the evaluation of high-power microwave coupling phenomenology and effects on military hardware and systems.

In this paper we report about aspects of our HPM-test methodology, starting in Section 2 with the discussion of the HPM weapon parameter space. Section 3 is devoted to the important consideration of the essential coupling mechanisms.

With the aid of transfer functions we describe the interaction of electromagnetic (e-m) waves with a system. Starting with numerical simulations we present three different coupling measurements at low level with the passive system, followed by cw- and pulse - tests at different power levels.

In Section 4 the influence of the coupled HPM energy in the system on its essential mission functions is investigated. Section 5 concludes our paper with a few words about hardening against HPM and aspects to use HPM as a means for defense.

2. HPM Weapon Parameter Space

There is a host of HPM weapon parameters. The parameter space covers frequencies from a few tens of MHz to tens of GHz, pulse widths from nanoseconds to hundreds of microseconds, pulse repetition rates from single pulse to thousands of Hz, peak power levels from megawatts to gigawatts. Also the polarization of the incident electromagnetic field and the angle of incidence are very important. Of course, the most effective choice of a parameter set depends on the system to be disturbed or destroyed, its exterior and interior characteristics and technology. Therefore, in some cases it is easier to harden a known system against HPM than to attack successfully an unknown system with HPM. This is due to the fact that it is very difficult to find out (within a few milliseconds) at which frequency an unknown enemy system could be most vulnerable. This task is related to the problem of target classification and identification on the basis of radar signal analysis and on the support of intelligence means.

Among the currently discussed concepts of possible HPM weapon systems the tunable phaser (**p**ulsed **h**igh-**a**mplitude **s**inusoidal **e**lectromagnetic **r**adiation) [1] might seem to be one of the most promising. It is appropriate for front-door and back-door coupling. The tunability range should be sufficient for all intended missions (if necessary at the expense of maximum power), and the repetition rates of HPM pulse sequences should cover the frequency range from 20 Hz to 20 kHz. As will be discussed below, tests with modulated cw irradiation of smart missiles and ammunition have shown that even irradiation of missiles at lower power with adjusted carrier frequencies and the right modulating frequencies strongly interfere with the control, guidance and tracking loops of the missile and, under special circumstances, lead to the interruption of the missile's attack.

3. Coupling

Smart ammunition and missiles typically have a number of electronics and sensors on board being necessary for a guided or an

autonomous flight mission. They normally have intended and inadvertent paths of microwave transmissions. An intended path of microwave transmission (front door coupling) is - e.g. - the subsystem mm W-seeker with the antenna system, or the IR-seeker. Almost all smart ammunitions need wings for the aerodynamic lift and for stabilization, and control fins to guide and maneuver the system. Barrel or tube launched systems require folded wings and fins which are deployed after the launch, partially through slots. For the initialization prior to the launch, umbilicals are necessary. All these system-specific designs act as antennas when excited by the HPM field and thereby intensively support the coupling to the inside of the system (back door coupling).

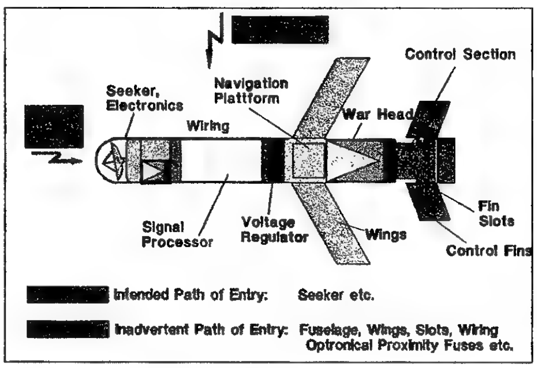


Fig. 3-1: Coupling paths

The coupling mainly takes place in three steps: The outer excitation of the system inducing currents and charges on the outer structure, the outside to inside coupling through apertures and via wings and fins or other antennas, leading to strong inferences with interior cavities and cabling and eventually, the transmission of the interior disturbances to sensitive electronics usually accompanied by the non-linear behaviour of circuit board elements. Those non-linear processes are necessary to make the low-frequency content of amplitude-modulated signals to appear in their spectra (demodulation).

The coupling of an incident e-m wave to same target, into its interior, to the cabling and the electronics is conveniently described in terms of cross sections or of transfer functions. Here we prefer the notation of transfer functions $T(f)$ which may be defined as:

$$T(f) \equiv V_i(f)/E_P^{inc}(f) \qquad (1)$$

In this definition $E_P^{inc}(f)$ denotes the amplitude of the incident continuous wave with frequency f and a given polarization P at the position assigned for the target. The illumination of the target by that wave causes the voltage V_i across a port of a vulnerable electronic device inside the target, after steady state conditions are achieved. To investigate the coupling into the target's interior one usually factorizes the problem into an exterior and an interior part [2].

$$T(f) = T_i(f) \cdot T_e(f) \qquad (2)$$

The exterior transfer function T_e is the ratio of the actual field or current surface density at a small aperture or narrow slot on the outside of the target hull over the amplitude of the incident wave. Taking polarization indices into account T_e is a complex matrix and T_i a complex vector.

The interior transfer function T_i is the ratio of the voltage V_i to that external field or current surface density. If there are several penetration paths into the target each path gives rise to a term like (2). The complete results for $T(f)$ is then given by the sum over all the individual paths.

The factorization (2) will be of practical importance if the penetration path from the outside region to the interior region is narrow, e.g., only a few narrow slots or small apertures perforate the metallic target hull. Under this condition T_e will change only very little if all slots and apertures are closed and only the exterior of the target is seen by the incident wave. If the exterior geometry of the target is simple enough an analytical

treatment may be manageable [3, 4] for a resonance decomposition of the exterior transfer function

Frequently one prefers to measure currents I_w at a port of the device of interest instead of the voltage V_i. In these cases one refers to transfer admittances rather than transfer impedances. The maximum magnitude of the transfer admittance as a function of frequency constitutes an upper bound for the induced current relative to the incident e-m field whatever spectrum is used for the incident pulse. Obviously, in order to get close to the maximum current one has to tune the incident signal precisely to the highest resonance in the transfer admittance and limit the bandwidth to about the halfwidth of the resonance peak.

The maximization of the response at the entrance of a sensitive electronic device is one important aspect to disturb a system. Not less important is the pulse repetition frequency of the incoming pulse-train (burst). This frequency may become effective after a non-linear process on a circuit board. If it meets a system's immanent frequency the interior exchange of signals and data can easily be influenced. Moreover, the probability to perturb a smart system is increased by a proper adjustment of the (single) pulse length and the burst duration.

3.1 Modeling of Coupling

With regard to Equation (2) the coupling problem can be decomposed into two parts. First, there is the interaction of the e-m wave with the exterior of a system, inducing surface currents and charge densities on its surface which drive small antennas and apertures. Secondly, the outer currents and charges serve as sources for the interior coupling. They may excite, e.g., cavity resonances and quasi TEM-resonances on short circuited cables inside the system.

It is very difficult to describe this e-m interaction with a system analytically. However, in many cases it is possible to model the considered system or parts of it with the aid of simple geometrical shapes, like cylinders (with hemispherical endcaps [4]), spheres and cubes. Then analytical formulas can be derived, and the excitation modes and their corresponding frequencies can be calculated. This serves as a first rough estimate.

More accurate results are obtained by the application of advanced numerical codes. We use the numerical MoM code CONCEPT [5] and demonstrate with an example of a (real) missile model the outer and interior coupling [6].

The result of the outer coupling to the missile is displayed in Figure 3.1-1. The incident e-m wave is horizontally polarized, i.e. the $\vec{E}$-field vector is parallel to the fuselage, the wave vector and the $\vec{B}$-field vector are orthogonal to the fuselage. Different colours on the surface of the missile indicate higher (red) or lower (blue) current magnitudes. The wavy current structure corresponding to the longitudinal "(λ/2)-mode" (maximum in the middle, minima at the top and bottom) and the azimuthal cosφ-dependency is obviously recognized. Knowing that the missile is illuminated at 200 MHz one concludes its length of about 0.75 m.

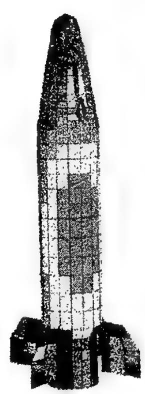


Fig. 3.1-1: Current distribution on the surface of a missile

The interior coupling is much more complex and complicated than the outer one. Every numerical model, therefore, can only cover certain physical aspects of interactions, like, e.g., cavity resonances, quasi-TEM

resonances on conductors, and effects of absorbing (and non-conducting) material inside the missile or of protection measures. Appropriate damping techniques rely, e.g., on suppressing resonances by the use of more (2 - 3 dim.) dimensional resistor arrays, preferably positioned at field maxima for cavity modes, and by loading the conductors with resistors and (in some cases) inductors at the locations of current maxima.

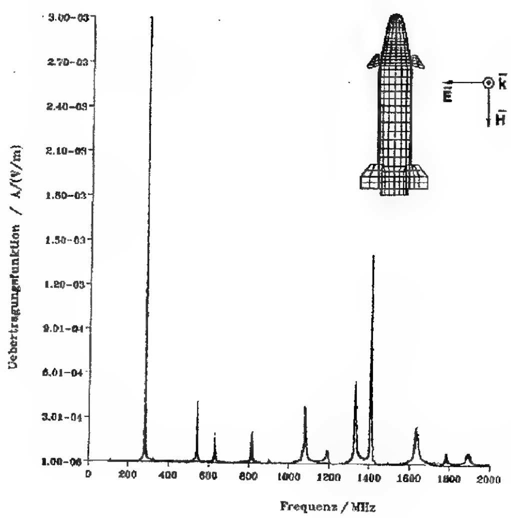


Fig. 3.1-2: Cable resonances

Figure 3.1-2 exhibits well-pronounced resonances at both ends of a short circuited wire. Again, the incoming e-m wave hits the missile from broadside with vertical polarization ($\vec{E}\,\|$ to the fins, $\vec{B}\,\|$ to the fuselage). A dominant TEM-mode occurs at about 300 MHz indicating a cable length of about 0.5 m. Interactions inside the missile between cables and the missile's wall or other structures cause shifts of the positions of the resonances from their theoretical values and resolve degenerated TEM- and cavity-eigenresonances. Usually, TEM-resonance peaks are higher than those which are originated in cavities.

Of course, the application of a numerical simulation to complex systems has its limitations and does not replace an experiment. It serves, however, as one basic tool to facilitate the interpretation of physical processes, and as a first guess for the experimental results to be expected.

3.2 Coupling Measurements of the Passive System

On the basis of the results of our analytical and numerical calculations one can already make a first guess at which system resonances maximum coupling in the experiments could take place. Besides the validation of the applied numerical code, the main goal of the low power (microwave) measurements at a passive system is to identify typical resonance frequencies at which the electronics of the active system may be disturbed. Of course, the resonance peaks occurring in the transfer functions of a system depend on the kind of excitation (free-space illumination, free-field irradiation, direct current injection, or excitation in an extended coaxial system, etc.), its polarization, the angle of incidence, and the location of the sensors (B-dot, D-dot). Our main interest was concentrated on the measurement of field induced currents or open circuit voltages on selected cables or pins. The cables mostly were short circuited at both ends and occasionally terminated with 50 Ω resistors.

In the following we show three different excitation methods of three smart missiles and their responses on interior, short circuited cables and open circuit voltages at the rear end [7].

In Figur 3.2-1 a missile is irradiated by a log-periodic antenna in an anechoic chamber. With vertical polarization the $\vec{E}$-field is parallely oriented to the fins and the $\vec{B}$-field parallely to the fuselage, respectively. In the transfer function (Fig. 3.2-2) we recognize a host of peaks, beginning at frequencies lower than 0.5 GHz up to 3.5 GHz, with quality factors lower than ten.

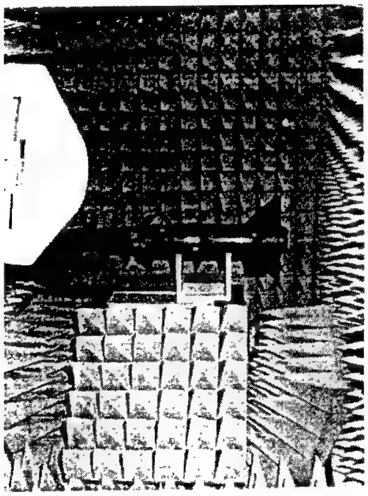


Fig. 3.2-1: Missile irradiated in an anechoic chamber

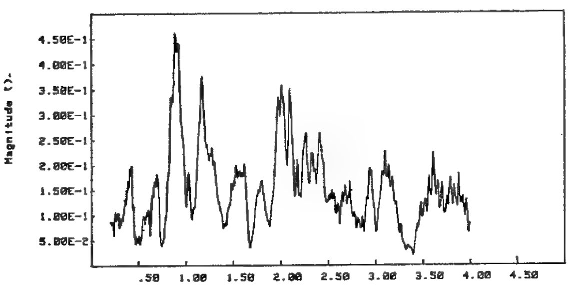


Fig. 3.2-2: Open circuit voltage

Besides a global illumination of a system, one may also decide - due to the lack of an anechoic chamber and the necessary equipment - to perform local coupling experiments. Certainly, in these cases one only excites single coupling paths. Nevertheless, one obtains useful results, in particular, when there are only a few points of entries (POEs). An "in-phase" superposition of the responses (at one measuring point) obtained by the coupling through (almost) all POEs can serve as an upper bound for a global field excitation.

Figur 3.2-3 depicts a direct current drive into a fin corresponding to an $\vec{E}$-field excitation of the fin. Since the fin is not connected to the missile's hull, the applied current flows into the interior. There it causes perturbation currents and voltages into the cabling.

Fig. 3.2-3: Direct current drive into a fin

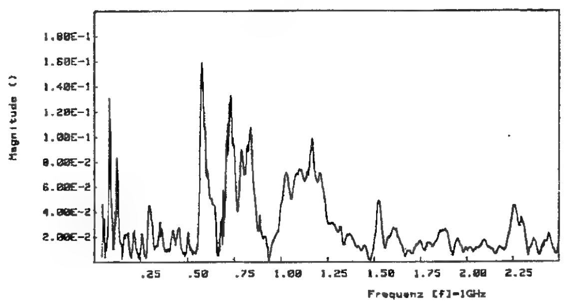


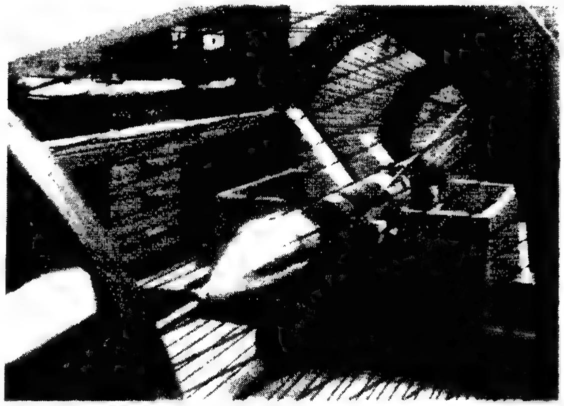
Fig. 3.2-4: Short circuited current

The transfer function in Figure 3.2-4 shows dominant current peaks at "lower" frequencies (cable resonances). Above 1.5 GHz the values decrease. In this case we chose an averaged magnetic field, generated by the fin-induced current, as reference.

Our third kind of excitation takes place in an extended coaxial system in which the interior conductor is partially replaced by the missile. This is not a well matched system. The characteristic impedance changes with location (from 50 Ω to a value of about 377 Ω), due to the variation of the wave guide's outer shape, the thickness (cone-tops at the near and far end of the missile) of the "interior conductor" and the TEM-field perturbing wings of the missile.

Reflections occur and lead to standing waves. Thus, besides the TEM-ground mode we expect a couple of other (higher) modes. The

main components of the $\vec{E}$-field are parallel to the fins, whereas the $\vec{B}$-field is perpendicular to the slots.



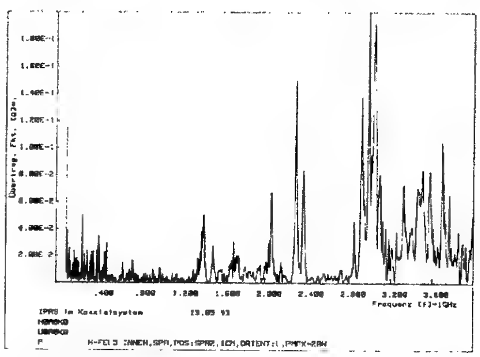


Fig. 3.2-5: $\vec{B}$-field in a cavity of the missile

Figure 3.2-5 shows the response of the missile mainly at "higher" (above 1 GHz) frequencies, indicating a $(\vec{B}-)$ field measure ment in some cavity of the missile. The reference field was determined by an averaging procedure of a field mapping along the interior conductor when the missile was absent.

3.3 Coupling Experiments with Active Smart Systems

The coupling experiments with active smart systems are based on the analytical and numerical investigations and also on the results achieved from the coupling experiments with the passive systems. These introductory coupling considerations and experiments provide the most interesting and also "dangerous" frequency ranges for the smart systems, show where the most critical coupling paths are, and give information about coupled currents and voltages on the system's internal wirings.

So the provided analytical, numerical and experimental results of the passive system enable experiments with the active system in an effective way with respect to time as well as radiation parameters.

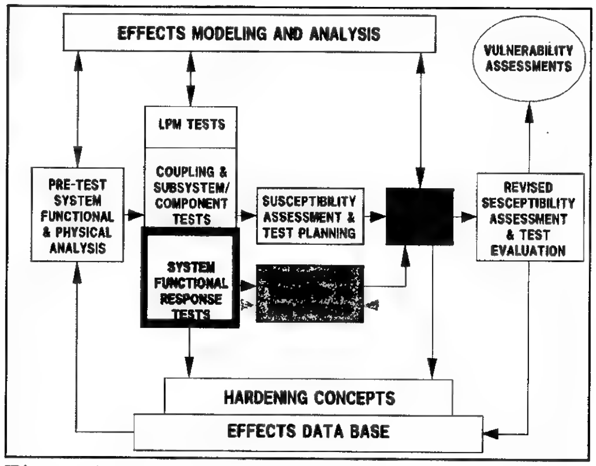


Figure 3.3-1: Linkage of HPM-considerations

Only susceptibility investigations with the active system show how the guidance and control loops, including electronics and sensors, can be interfered.

3.3.1 The Guidance and Control System of Smart Defense Systems

The guidance and control components are tasked with guiding the missile or smart ammunition after stabilization to a target area and acquiring a target with subsequent final homing. The guidance and control loop of smart ammunition is designed with different layers of control loops having different tasks. These control loops are more or less sensitive to electromagnetic radiation interference.

The complex guidance and control system of smart ammunition shows a hierarchical structure and exists of a number of cascaded loops.

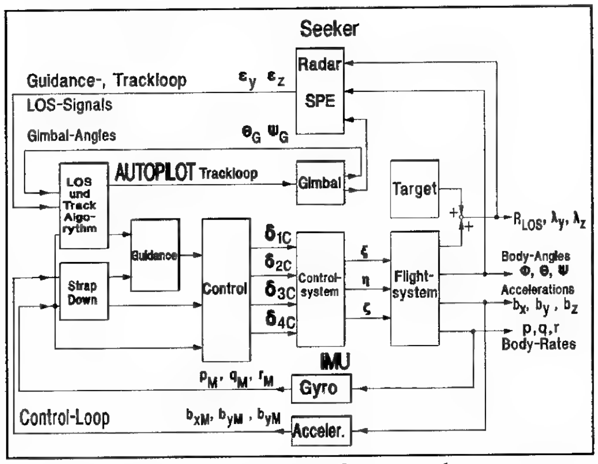


Figure 3.3.1-1: Structure of a complex guidance and control system

Among these, the most interesting and important ones are the ***guidance loop***, the ***control loop*** and the ***track loop***.

The **control loop** is tasked to ensure roll control in the three axes (roll, yaw and pitch). This includes the stabilization of the roll movement (attenuation), the achievement and keeping up of an inertially predetermined flight attitude (attitude hold), the control of the angle of incidence of ammunition to ensure the required accelerations.

The **guidance loop** is superposed on the previously described control loop. It is responsible for the Center of Gravity (CoG) movement (trajectory).

After target acquisition the guidance signals will be computed, based on the target miss distance data ey and ez as measured by the seeker (deviations from the aimpoint in the seeker field of vision). In order to minimize the miss distance values, also in the case of rapidly moving targets, the proportional navigation is used as a guidance method. The line of sight rate data needed for this guidance law are estimated by means of a special algorithm (LOS algorithm).

The **track loop** is the most sensible and the main loop during the end game. A constant line of sight is required between the seeker and the target. Therefore, seeker frame system-to-target tracking is required. Since the position of the aimpoint in the seeker field of vision (which is only +/- 1.5 degrees) is determined by both, the target movement and the system's in-flight movement. The tracking algorithm must use the roll rate measured via the IMU (inertial measurement unit). The processing of roll rate measurement data subject to interference will, however, cause malfunctions to the seeker tracking process which may, in the worst case, result in target loss and, hence, system end game failure.

3.3.2 Test Set-Up

To conduct irradiation tests with the active system, typically an internal power supply which normally is a rechargeable battery system, has to be incorporated to operate the system. The most important system signals are led to a data acquisition system using an opto-coupler module with fiber optics. The internal power supply and the signal transmission via fiber optics ensures that no abnormal galvanic linkage is brought to the system. To simulate a real flight mission which is typically a defined end game scenario, a target simulator is also involved in the test set-up.

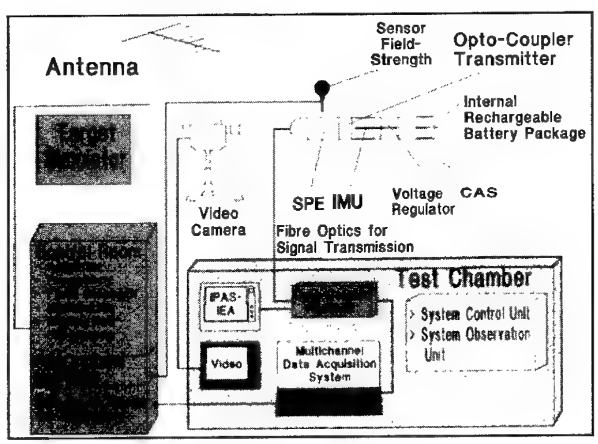


Figure 3.3.2-1: Test set-up

Prior to the irradiation tests a test matrix has to be written, where all relevant test parameters like frequency range, angle of incidence (AoI), fieldstrenth (FS), polarization (Pol), modulation (Mod) or pulse repetition rate (PRR), continuous wave (CW) or pulsed radiation (PR) and pulsewidth(PW) have to be considered in accordance with the

introductory analytical, numerical and experimental investigation results.

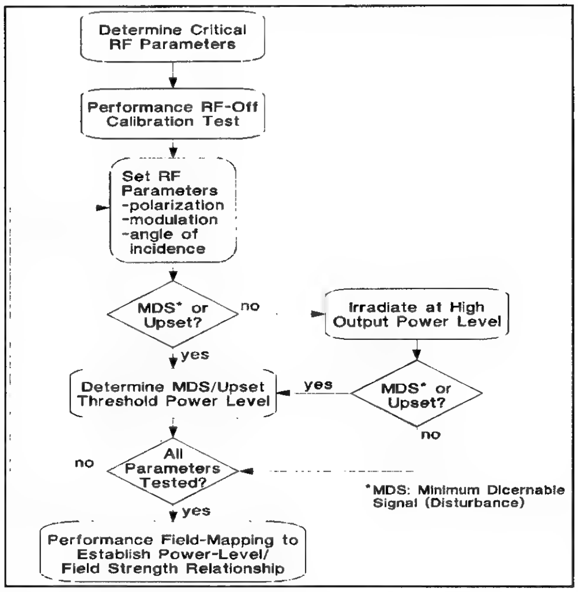


Figure 3.3.2-2: HPM-EMI test methodology

3.3.3 Irradiation Tests

The irradiation tests with the active smart system typically are divided into Low Power Microwave Continuous Wave **(LPM-CW)-**, Low Power Microwave Pulse **(LPM-Pulse)-** and High Power Microwave **(HPM)-**tests.

The ***non-destroying LPM-CW*** susceptibility tests are conducted to detect the critical frequencies for the considered system as a function of the various radiation parameters and the coupling paths.

The ***non-destroying LPM-Pulse*** tests with the acitive system provide information how the system reacts in case of pulsed radiation. The most important and different radiation parameters are PRR and PW.

The ***HPM*** irradiation tests with smart defense systems are normally conducted under non-destroying aspects due to the immense costs in case of burn-outs of electronic and sensor elements. For ***destroying HPM*** irradiation tests generic electronic systems and wiring systems with typical housings and potential coupling paths are designed and built to get information with respect to permanent damage levels of relevant electronic circuits.

The advantage of those systems is that all information concerning electromagnetic effects are known. This begins with the design process of the mechanical and electronical components with CAD/CAE tools, where the data package can be used directly for numerical EMI considerations with respect to structure and wire resonances (induced voltages and currents) and network analysis of the electronic circuits.

LPM-CW and LPM-Pulse Test Results

We are looking at susceptibilty possibilities of smart systems. Normally systems are interferable in a broad frequency band. This means that one must not hit a very precise frequency for back door coupling. The various resonance peaks can be separated into structure (body) and wire resonances and into fin and slot resonances.

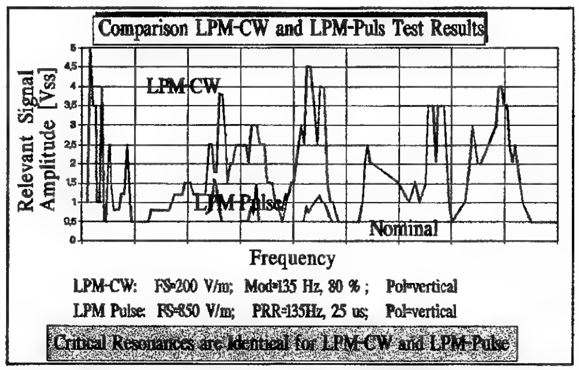


Figure 3.3.3-1: LPM-CW and LPM-pulse test results

The disadvantage of the LPM-Pulse tests is that not sufficient energy is provided to the system. Over a wide range of the possible frequencies the MDS-values could not be exceeded.

The pulse width (***PW***) (in the case of LPM-Pulse tests) has a strong influence on the signal interference of relevant guidance and control signals.

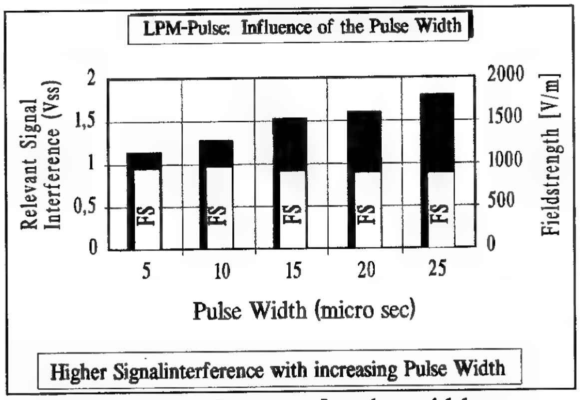


Figure 3.3.3-2 Influence of pulse width

The ***PW*** and, of course, the ***FS*** have a direct relationship with the signal interference and the provided energy to the system. The guidance and control signals react on the provided energy. It cannot yet answered, if this statement is also valid for real non-destroying HPM-Pulses.

Another important radiation parameter is the modulation frequency (***MF***) for LPM-CW tests or the ***PRR*** for LPM-Pulse tests. The waveform of the modulation (sinus, square, etc.) does not show any significant influence on the signal interference.

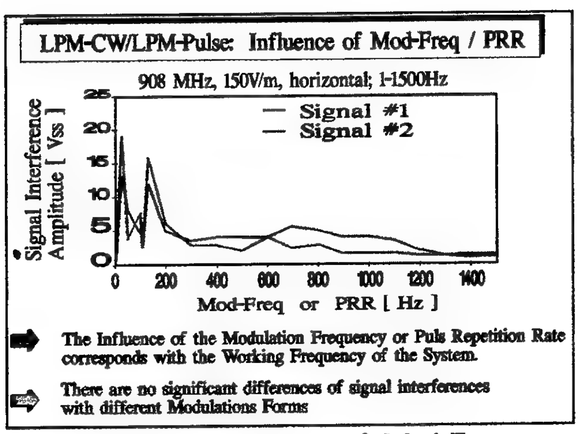


Figure 3.3.3-3: Influence of Mod-Freq. or PRR

The pulse repetition rate or the modulation frequency show the biggest influence if they correspond with working frequencies of the guidance and control elements. Nevertheless it is not necessary to meet a very precise PRR. The typical bandwidth for smart defense devices where electromechanical subsystems (seekers, navigation systems or fin control systems) are involved is located in the region of less than 150 Hz.

Other radiation parameters are Angle of Incidence (AoI) and Polarization (Pol) which have to be considered during susceptibility tests of smart defense systems.

The ***AoI*** typically shows no significant influence on signal interference.

In some cases the ***Pol*** is an important parameter.

As a summary we can state that non-destroying LPM tests are able to provide most important information with respect to the susceptibility of considered systems and reveal also the critical coupling paths.

HPM Results for Non-Destroying Tests

The most different irradiation parameters of HPM tests are the achievable high fieldstrength and the limited pulse width (compared to the LPM-Pulse tests). Available HPM-simulators are able to realize PRRs up to 100 Hz and FSs of more than 100 kV/m at the test objects.

For non-destroying HPM-tests the FS is typically limited to about 30 kV/m at the smart defense systems. Higher FSs could cause permanent damage (burn outs) in electronic circuits.

Actual tests were conducted with a fixed PPR of 1Hz.

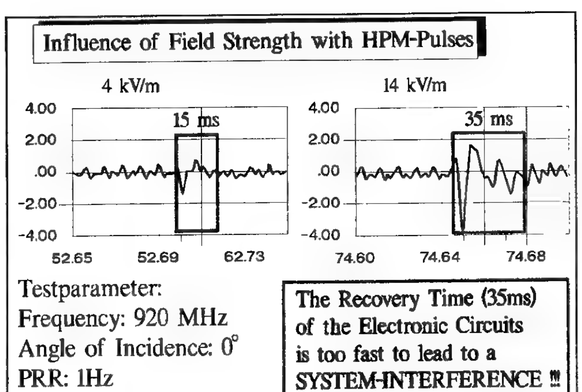


Figure 3.3.3-4 HPM test results

We see that the signal interferences of smart defense systems can be compensated within a

recovery time of about 25 to 35 ms if the system is irradiated with non-destroying HPM pulses and a PRR of 1 Hz.

The signal interference of course depends on the energy provided to the system. The tunable parameters are FS and PW.

If the PRR would be increased to about 25 to 35 Hz, a constant significant signal interference could be achieved over the whole (extended) radiation time. In the next section it will be shown how the flight path of a system can be influenced in case of signal interferences.

The critical frequencies are almost identical with the frequencies measured during the LPM-CW tests.

The ***comparison*** of the signal interferences caused by ***LPM-CW and HPM*** tests again shows that the provided energy is the major key player in case of non-destroying irradiation tests.

At a comparable radiation frequency and AoI but at different fieldstrength combined with a significant difference of the pulse repetition rate (or modulation frequency) the energy provided to the system is for LPM-CW about 48mJ/m²/Hz and for HPM about 16mJ/m²/Hz.

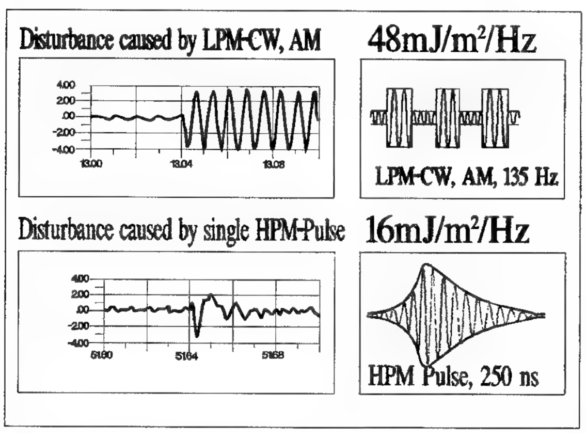


Figure 3.3.3-5: LPM-CW and HPM energies

Effects due to ***destroying HPM irradiation*** in smart defense systems have to be considered separately and probably will show other major key players.

The non-destroying irradiation tests have shown that relevant guidance and control signals of smart defense systems can be interfered. But what does this mean for the mission these systems are designed and built for?

To answer this question the measured signal interferences caused by LPM and HPM radiation have to be considered in a flight path simulation programm (6 Degree of Freedom).

4. System Flight Simulation

The analytical, numerical and experimental investigations with the passive and activated system have shown a lot of resonances.

The electromagnetic field causes resonances on the surface of the smart system. Surface currents and -charges interact with the cavities of the system via the fins and the slots. These perturbations act in turn as secondary radiation sources on the wirings and electronics of the system with a potential system interference.

Not all resonance-excitations cause an interference in the electronics. The next question which has to be answered is which interferences of the electronics cause a malfunction to the mission success of the system. Therefore, the measured interferences of the various guidance and control signals have to be fed into the 6-DOF (6-Degree of Freedom) flightpath simulation program to find the real interference of the flight mission in dependence of the exterior field conditions.

According to Fig. 3.3.1-1, the most sensitive signals in the guidance and control loop of a smart defense system can be found in the track loop or in the interference with the gimbal signals which influence the line-of-sight signal and lead to a loss of the target.

A really measured signal interference was superimposed with the guidance and control signals within a 6-DOF flight path simulation.

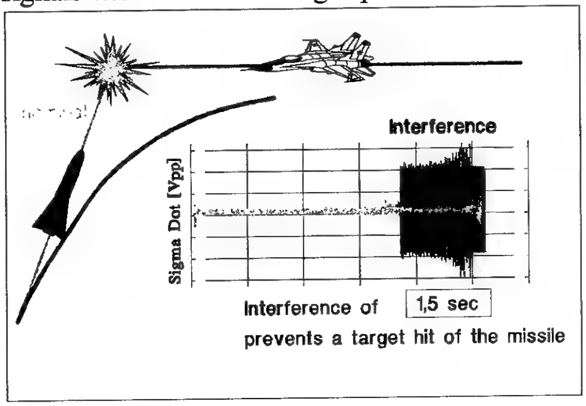


Figure 4-1: Interference of system's mission

The result shows that the measured signal interference causes a malfunction in the system's mission. A target impact could be prevented.

5. Conclusion

The threat for smart defense systems caused by HPM becomes more and more important. Worldwide research and development activities in the area of HPM systems make it necessary to investigate the deployed systems with respect to their HPM susceptibility and to evaluate hardening possibilities.

Hardening Aspect

The threat of HPM has to be considered already in the design process of smart systems. The hardening of wrongly designed systems is very cost-intensive and sometimes not possible.

The EMI-HPM aspects should be a fixed part of the system's design process with a closed loop character.

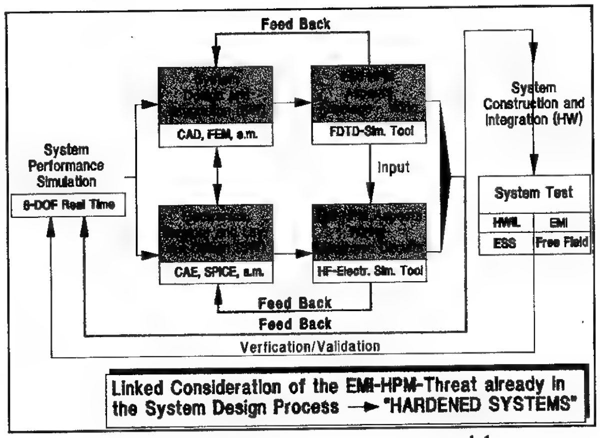


Figure 5-1: Design process must consider already the HPM threat

The system design and integration data have to be used to analyze a system with the aid of analytical and numerical methods. The results have to be used to improve the system design (feedback) with respect to coupled electromagnetic fields up to the level of the system-wiring.

In parallel to this the electronics and sensors are designed. The electronic circuits have to be assessed with respect to the HPM-susceptibility using the calculated wire-currents/voltages.

The combined results from the system design/integration level and from the electronics level have to be used in the flight path simulation to see the effects on the mission performance depending on the external HPM-scenarios.

Having received a satisfactory system design also with respect to the HPM-threat the system construction process can be started. Nevertheless, experimental investigations are necessary to validate and verify the hardened system and the simulation tools.

Defense Aspect

The susceptibility of smart defense systems against high power microwaves presents besides a threat also a chance. Smart missiles, smart ammunition, communication and surveillance systems are susceptible to HPM. Thus, one may use HPM systems for the defense of our own military systems or to attack enemy systems. HPM systems can be

deployed as stationary ones, they can be mobile, but also ammunition types are possible. One possible application can be seen in a SEAD role (Supression of Enemy Air Defense)

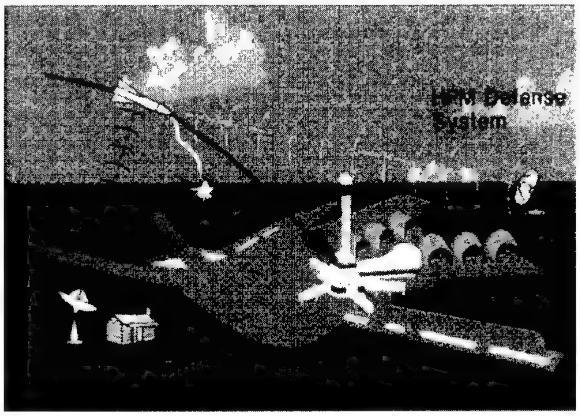


Figure 5-2: HPM involved in a SEAD system

We conclude that HPM-like systems may become interesting and promising weapon systems in the future. However, as we have shown in this paper, we are still at the beginning of the investigation of the very complex and difficult problems concerning HPM interactions and protection measures against HPM. The results of the research during the next decade will probably show us the wide variety of possible HPM-weapon applications.

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Tendances de la Guerre Electronique Air
Une Perspective Européenne

(An English version follows)

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1. SOMMAIRE

La guerre électronique est restée, jusqu'à maintenant, un domaine où chaque grande nation a cherché à se préserver une très large part d'autonomie. L'Europe se faisant, les budgets se contractant, il est raisonnable de penser que cette situation va maintenant rapidement évoluer. C'est en tout cas un scénario auquel l'Industrie se doit de se préparer, même si la décision reste éminemment politique.

Dans cette hypothèse, la première considération développée est que la guerre électronique doit être abordée comme un tout. Elle ne doit plus être traitée programme par programme et au niveau des seuls équipements. Elle doit au contraire aller de l'acquisition du renseignement, permettant de définir les menaces, à la simulation technico-opérationnelle, permettant de spécifier les systèmes et équipements, puis aux moyens d'évaluation et essais et enfin, aux supports à l'utilisation. Elle doit également traiter toutes les composantes spectrales des menaces connues ou prévisibles.

Une seconde considération est que la contrainte primordiale des coûts, jointe aux difficultés techniques que pose la cohabitation sur un aéronef de différents systèmes, font que la guerre électronique ne peut plus être traitée isolément. Il devient de plus en plus nécessaire de partager des fonctions techniques entre systèmes, de partager les ouvertures rayonnantes, de partager le temps.

Un premier pas est actuellement franchi avec l'avionique modulaire numérique. D'autres pas sont à franchir dans les domaines des senseurs, des antennes.

Enfin, et il s'agit là de considérations qui concernent d'abord l'Industrie, mais qui ne peuvent pas laisser les Etats indifférents car il en va de l'indépendance de l'Europe, il demeure indispensable de conserver la maîtrise de filières technologiques clés, pour lesquelles les applications commerciales n'atteignent pas encore un volume suffisant ou bien au contraire ont des cycles de renouvellement peu compatibles des programmes militaires.

2. INTRODUCTION

Je vais proposer à votre réflexion et tenter d'illustrer, pendant ce court exposé, trois messages, qui tous les trois concourent à la même affirmation : Nous, industriels européens, unissons nos efforts pour présenter à l'Alliance une alternative industrielle européenne face à l'offre industrielle américaine.

Premier message (Pl. 1) : La guerre électronique a évolué. Elle doit être abordée comme un tout, allant de l'acquisition du renseignement à la mise en oeuvre des Contre-Mesures. L'Europe a, dans ce domaine de réels points forts, mais aussi des lacunes qu'elle peut, en s'unissant, combler.

Second message (Pl. 2) : La réduction des coûts des systèmes est un impératif. La standardisation de modules, leur partage entre différentes fonctions et la recherche d'effets de quantités apportent des premières réponses à cette exigence. Une démarche européenne est maintenant engagé dans ce sens. Elle doit être poursuivie et amplifiée.

Troisième message (Pl. 3) : La guerre électronique fait appel à des technologies spécifiques. L'Europe a aujourd'hui la maîtrise de ces technologies clés. Elle doit non seulement savoir préserver cette maîtrise mais aussi savoir traiter de domaines nouveaux et prometteurs. C'est peut être là que résident ses plus grandes faiblesses mais il n'est pas trop tard pour réagir.

3. LA GUERRE ELECTRONIQUE A EVOLUE ...

3.1 Les grandes phases de l'évolution (Pl.4)

Sans vouloir retracer l'historique de la guerre électronique, on peut dire, pour synthétiser, que l'on est passé progressivement de la notion d'équipements élémentaires très typés - détecteurs d'alerte - brouilleurs ... ayant leurs technologies propres, souvent rajoutés en cours de vie des avions, à la notion de systèmes intégrés, faisant appel à des fonctions techniques banalisées, adaptables à différentes missions par simple programmation et pris en compte dès la conception initiale de l'avion.

A titre d'exemple de banalisation de fonction, on peut citer la détection d'alerte (R.W.R.) qui a dû progressivement rallier les performances de sensibilité, sélectivité et précision de mesure des analyseurs d'ELINT et fait maintenant appel, pour partie, aux mêmes technologies. A titre d'exemple encore, les mêmes antennes à modules actifs (TR modules) peuvent être indifféremment utilisées en fonction de détection et de brouillage.

3.2 Guerre électronique Air : Vers un système de systèmes (Pl. 5)

Parallèlement, la veille distinction technique entre les émissions de communications, à caractère continu et en ondes

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métriques et les émissions radar, à impulsion et ondes centimétriques s'est effacée. L'importance de la connaissance a priori des caractéristiques des menaces à détecter puis identifier a été mise en évidence, conduisant à fermer, dans des temps de plus en plus courts la boucle constituée par l'acquisition du renseignement, la programmation des bibliothèques des équipements avant mission et l'exploitation des informations recueillies durant la mission.

Parallèlement encore, et face à l'apparition de systèmes multisenseurs, la composante optronique a dû venir compléter les moyens plus traditionnellement mis en oeuvre dans le domaine des ondes radar.

Ce sont donc des **systèmes globaux** de guerre électronique que l'on pourrait appeler système de systèmes qu'il faut maintenant concevoir, en partant de la connaissance que l'on peut avoir des menaces (différents systèmes Sol-Air et Air-Air adverses), des missions et de l'environnement radioélectrique rencontré lors de ces missions pour programmer les systèmes d'autoprotection ou de neutralisation de défenses puis exploiter les informations recueillies pendant les missions.

Ceci suppose de puissants moyens de simulation technico-opérationnelle, d'acquisition de renseignements, de préparation de mission et d'exploitation des résultats de missions. A titre d'exemple cet ensemble de simulation opérationnelle SPARTE (Pl. 6) permettant de simuler le comportement de systèmes d'autoprotection d'avions pénétrant dans une zone défendue par divers systèmes d'armes.

Ceci suppose également des moyens très spécifiques d'aide à la conception, à l'intégration puis à la caractérisation de ces systèmes. (PL. 7)

A titre d'exemple, les moyens de modélisation SARGASSE permettant d'évaluer le rayonnement d'antenne sur avion (réflexions, diffractions ...), la base d'essais MENGAM permettant la mesure de ces rayonnements sur avion réel ou encore la chambre anéchoïque BRETIGNY permettant l'évaluation dynamique des systèmes face à de multiples menaces.

3.3 Un point fort européen : Les systèmes intégrés (Pl. 8)

Un point qui mérite particulièrement d'être souligné est l'effort porté, en Europe, sur l'intégration des systèmes d'autoprotection. On a cherché et est parvenu non seulement à rendre compatibles entre elles les fonctions de détection et brouillage en minimisant les redondances d'équipements mais aussi et surtout à les rendre compatibles des autres fonctions de l'avion telles que radar, C.N.I. ... .

Un exemple de système intégré, le système d'autoprotection SPECTRA de l'avion Rafale illustre ce propos, et des exemples équivalents pourraient être pris sur l'Eurofighter, les Mirage 2000 ou les Tornados mais aussi sur les hélicoptères Tigre, NH 90 ...

3.4 Deux lacunes européennes (PL. 9)

Si l'Europe dispose donc d'une très large panoplie de moyens lui permettant de traiter des systèmes de guerre électronique complexes, elle a néanmoins quelques lacunes.

Par exemple, en matière de renseignement électronique, la composante spatiale n'est encore qu'embryonnaire. C'est pourtant elle qui permet l'accès à n'importe quelle région du globe de façon permanente.

Par exemple encore, en matière de brouillage, si les systèmes d'autoprotection des aéronefs ont été très développés, les brouilleurs d'escorte ou stand-off destinés à neutraliser les radars de veille et désignation d'objectifs, manquent toujours dans la panoplie européenne. Ils semblent pourtant avoir connu un usage intensif de la part des forces américaines lors des derniers conflits, et ce au profit de l'ensemble des forces alliées.

Dans ces deux exemples donnés, les techniques de base - Antennes à balayage électronique, mémoires numériques de fréquences ... sont disponibles en Europe, et les enjeux financiers, s'ils peuvent être difficiles à supporter par un seul pays, ne sont certainement pas hors de portée d'une Europe unie. Ils se situent en effet environ un ordre de grandeur (c'est à dire un facteur 10) en dessous des grands programmes d'actualité.

Les besoins existent. Les techniques sont disponibles. A nous, industriels européens de montrer que nous savons mettre en place les structures transnationales capables d'établir une offre, de la confronter aux besoins opérationnels, de la rendre compatible des contraintes budgétaires et, en final de réaliser les programmes décidés.

4. IL FAUT REDUIRE LES COUTS (Pl. 10)

Sur ce sujet, l'unité de vues au niveau de l'Europe comme au sein de l'Alliance est parfaite et la même exigence est exprimée de tous côtés.

Que peut donc proposer l'Industrie européenne pour répondre à ce besoin.

4.1 Recherche des effets de volume

Une première voie, passe par la recherche des effets de volume en production, qui suppose elle même une convergence des besoins.

Bien sûr, et le sujet a déjà été largement commenté, cet effet de volume est d'abord à rechercher du côté des applications commerciales - ou duales, avec d'indéniables avantages sur le coût des approvisionnements initiaux mais aussi de sérieuses difficultés dues aux cycles de vie très différents entre produits militaires et civils - 3 à 5 ans dans le premier cas - 15 à 20 ans dans le second.

Ce pas a néanmoins été franchi en ce qui concerne les composants courants et la très grande majorité des composants numériques (processeurs et mémoires). Des études ont été conduites pour déterminer dans quelle mesure les enrobages plastiques utilisés dans le civil pouvaient prendre la place des boîtiers céramiques, avec des résultats positifs pour un certain nombre de procédés d'enrobage.

Mais cela ne résout pas, et de loin, tous les problèmes que pose la guerre électronique avec ses besoins spécifiques que sont par exemple les très larges bandes hyperfréquences, la séparation de signaux sur de très grandes dynamiques, la rapidité de réaction. Et les composants, s'ils représentent souvent une part déterminante du prix des équipements - 40 à 50 % - ne constituent pas le seul axe sur lequel il faut porter

l'effort.

Pour aller plus loin dans la réduction des coûts, c'est au niveau des architectures des systèmes qu'il faut agir avec comme objectifs l'utilisation de modules standardisés, multiprogrammes, et le partage des ressources entre différentes fonctions.

4.2 Avionique modulaire intégrée : La démarche européenne (PL. 11)
Un premier pas a été franchi dans le domaine des traitements numériques avec la démarche "Avionique Modulaire Intégrée", appliquée à notre connaissance sur le programme F22 et qui fait en Europe l'objet d'une démarche conjointe de l'Allemagne, du Royaume Uni et de la France dans le cadre de l'ASAAC - Allied Standard Avionics Architecture Council.

A ce jour, et après une première phase de travaux conduite avec les Etats Unis, ces trois pays se sont accordés sur un programme de travail commun devant, dans les 5 ans à venir, permettre de définir et valider par des démonstrations des normes et standards applicables aux traitements numérique de signal et données des avions d'armes. Par rapport aux programmes américains de même nature. Pave Pillar puis Pave Pace - L'accent est particulièrement mis sur l'emploi de COTS - Commercial off the Shelf - avec l'objectif de pouvoir, au cours de la vie d'un programme, s'accommoder des composants matériels et logiciels apparaissant sur le marché sans remise en cause des acquis antérieurs, et particulièrement des validations de logiciels opérationnels au sol et en vol.

Ce programme, qui devrait être lancé à la mi-année a conduit les Services Etatiques et les Industriels des 3 pays concernés à de nombreux échanges et à une convergence de vues sur les travaux à accomplir.

4.3 Mise en commun des efforts : un autre exemple (Pl. 12)
Cette démarche européenne n'est pas la seule du genre. Les mêmes objectifs de partage des coûts d'études et développement et de recherche d'effets de volume ont conduit les mêmes 3 pays à lancer en commun un programme d'antenne active pour radar aéroporté - l'AMSAR.

Une simple planche permettra d'illustrer l'effet de volume recherché. Elle représente l'évolution du coût des modules actifs en fonction des cadences de production en échelle log-log. On y observe une dégressivité de 2,5 par décade c'est à dire que les coûts sont divisés par 2,5 si le volume de production est multiplié par 10.

Cette très forte dégressivité s'explique par le fait que la maîtrise des performances des modules actifs impose une automatisation des procédés extrêmement poussée. De ce fait, la part prépondérante des coûts des modules est constitué par l'amortissement et l'entretien de l'outil de production plutôt que par la main d'oeuvre sur opérations récurrentes.

On observe sur cette planche que pour qu'une antenne active comportant un millier de modules actifs soit compétitive par rapport à une solution plus conventionnelle à base de tube et lentilles, il faut un minimum de production de 6 à 8 radars ou avions par mois, ce qui, à l'évidence ne correspond plus au besoin de nations prises isolément.

On y observe aussi tout l'intérêt qu'il peut y avoir à faire converger les différents types de modules actifs des différentes applications vers les mêmes procédés technologiques et outils de production. Cette démarche est en cours, notamment entre Elettronica - Italie - et Thomson-CSF en vue d'abaissement de coûts des modules actifs de guerre électronique des systèmes d'autoprotection du Rafale et de l'Eurofighter.

Ce sont des considérations de cette nature qui ont conduit les groupes Thomson-CSF et Daimler-Benz à mettre en commun leurs fonderies Arséniure de Gallium en créant une filiale commune, U.M.S. Et il est hautement probable que dès que les volumes de production le justifieront, une même démarche de mise en commun des lignes de fabrications et test de modules actifs devra être décidée par les grands groupes concernés.

Ces deux exemples qui viennent d'être donnés - Avionique numérique et modules actifs - qui débordent largement le strict domaine de la guerre électronique mais s'y appliquent complètement illustrent déjà la volonté des Etas et des Industriels européens d'unir leurs forces pour faire face aux défis qui leur sont lancés.

4.4 Autres perspectives (Pl. 13)
Mais on ne saurait s'en tenir là. La réduction des coûts impose que l'on pousse encore plus loin le partage des fonctions.

Ceci est particulièrement vrai pour les senseurs hyperfréquences, pour les antennes qui représentent la part prépondérante des coûts des systèmes , outre les problèmes d'implantation qu'elles peuvent poser.

La démarche "shared apertures" déjà engagée aux Etats Unis, et qui consiste à utiliser la même antenne ou surface rayonnante pour des fonctions radars, guerre électronique, C.N.I. est à la portée de l'Europe. Elle suppose, notamment du fait des contraintes de partage de temps entre fonctions qu'elle entraîne, des échanges approfondis sur le fonctionnement intime des systèmes - Cela n'est pas encore habituel en guerre électronique mais deviendra néanmoins indispensable si l'on veut poursuivre dans la voie de la réduction des coûts. Les grands Groupes Industriels pour leur part y sont prêts.

5. MAITRISE DU SOCLE TECHNOLOGIQUE

Si, comme il vient d'être dit, la guerre électronique du futur devra faire appel à de plus en plus de fonctions modulaires standardisées - Les traitements numériques en sont un exemple - on a des moyens partagés - Les antennes par exemple -, il n'en reste pas moins que des besoins spécifiques croissants continueront d'imposer la recherche de solutions technologiques novatrices.

5.1 Besoins spécifiques de la G.E. - Exemples (Pl. 14)
Trois de ces besoins spécifiques ont déjà été cités :

- La bande de fréquences à couvrir qui s'étend maintenant des ondes décamétriques (Radars antifurtivité obligent) aux ondes millimétriques.
- La sélectivité alliée à une large bande d'écoute instantanée, pour détecter des radars de plus en plus discrets et agiles sur de larges bandes.
- La rapidité de réaction, se comptant maintenant en nanosecondes.

L'Europe a, jusqu'à ce jour su maintenir, face aux besoins spécifiques de la guerre électronique le socle technologique nécessaire.

5.2 Trois exemples de maîtrise européenne de socle technologique (PL. 15)

Trois exemples significatifs peuvent en être donnés :

5.2.1 Les tubes hyperfréquences, et particulièrement les tubes à ondes progressives, couramment utilisés jusqu'ici dans les brouilleurs de radars. Il y a là un bon exemple où recherche à des fins militaires et recherche à des fins civiles se sont conjuguées pour doter l'Europe d'outils de conception et production de premier rang. (L'ensemble Thomson-CSF/AEG/ABB/Siemens est le n° 1 mondial dans le domaine). La contribution de la guerre électronique à cette performance doit être mentionnée. Par ses exigences propres, elle a conduit les chercheurs à déplacer les limites usuelles des tubes, offrant pour des applications moins contraintes d'utiles marges de sécurité.

5.2.2 Les filtres à ondes de surface, utilisés notamment pour constituer des récepteurs multicanaux (technique des récepteurs à compression ou bancs de filtres). Là encore, on a un bon exemple illustrant la retombée d'un effort de recherche initialement militaire dans le domaine civil. L'outil mis en place par Thomson-CSF dans sa filiale Microsonics pour sécuriser ses approvisionnements en filtres à ondes de surfaces a aujourd'hui une production tournée à 90 % vers le commercial - Filtres pour radiotéléphones ou sondes médicales.

5.2.3 L'arséniure de Gallium, pour lequel les besoins spécifiques de la guerre électronique, notamment en amplification bas niveau en ondes millimétriques ou en puissance large bande ont entraîné le développement de filières qui devraient elles aussi, mais à un terme plus éloigné qu'espéré, connaître de larges applications.

Cet effort de développement d'un socle technologique, l'Europe non unie a su, jusqu'ici, l'accomplir et, sur les exemples cités, les performances atteintes sont à l'état de l'art mondial.

Or, paradoxalement, ce que l'Europe non unie a su faire, elle semble, à l'approche de son unité peu décidée à le poursuivre.

5.3 Trois exemples de technologies nouvelles à maîtriser (Pl. 16)

Des besoins nouveaux se font jour en matière de guerre électronique. Des technologies nouvelles sont susceptibles de les satisfaire. Là encore citons trois exemples :

5.3.1 Les filtrages hyperfréquences - C'est, le plus en amont possible dans une chaîne de réception que l'on doit éliminer les signaux perturbateurs, dont le nombre s'accroît de jour en jour. ***Les filtres supraconducteurs*** apportent une réponse à ce besoin. Mais on n'est guère allé, en Europe, au-delà des démonstrations de laboratoire.

5.3.2 L'amplification de puissance aux fréquences basses : Il ne s'agit pas là d'un problème spécifique à la guerre électronique, mais le brouillage des télécommunications et des radars de veille, qui travaillent sur des bandes plus en plus larges imposent le recours à des amplificateurs multioctaves à très haut rendement. La technologie du Carbure de Silicium amène une réponse à ce problème et ouvre en outre d'intéressantes perspectives dans le domaine de la détection des missiles par leur rayonnement dans l'ultraviolet. Là encore, on n'a guère dépassé, en Europe le stade des démonstrations préliminaires.

5.3.3 Les traitements ultrarapides de signaux : Le multiplexage des sorties d'antennes, la mémorisation de signaux soit pour analyse fine, soit pour réémission après manipulation, le déport à distance de ces mêmes signaux seront des exigences de plus en plus marquées dans les futurs systèmes de guerre électronique. L'optique hyperfréquences apporte des réponses satisfaisantes à ces besoins et quelques applications - transmissions d'hyperfréquences par fibres optiques notamment ont déjà vu le jour. Mais il reste encore beaucoup à faire.

Ce sont trois exemples de besoins pour lesquels des voies technologiques existent et les compétences existent mais où l'Europe, aujourd'hui hésite, contrairement aux Etats Unis, en cachant son hésitation derrière de fausses bonnes raisons.

L'une de ces bonnes raisons est que ce sont les "programmes" qui doivent payer de tels développements pour bien montrer qu'ils servent à quelque chose. C'est oublier que la maîtrise de tels procédés nouveaux demande de 5 à 10 ans et qu'aucun programme - par ailleurs contraint budgétairement - ne peut prendre le risque de s'appuyer sur des technologies non prouvées.

Une autre raison avancée est que ce sont les industriels qui doivent prendre en charge le développement des filières dont ils auront besoin pour leurs produits futurs. C'est oublier là aussi que les Sociétés sont jugées aujourd'hui d'abord sur leurs résultats dans le court terme. Démontrer qu'une filière nouvelle sera économiquement rentable à l'échéance de 5 à 10 ans est dans ces domaines nouveaux plus que périlleux.

Pourtant, et les exemples donnés précédemment le démontraient, ce sont les besoins militaires qui ont entraîné le développement de filières nouvelles ayant maintenant des retombées dans le civil et non l'inverse et cela restera particulièrement vrai pour les applications de guerre électronique.

C'est dans ce domaine aux Etats de soutenir l'effort initial. Cela avait été compris dans le passé parmi les nations européennes et reste une règle aux Etats Unis. Souhaitons, et je m'adresse là plus particulièrement aux représentants des Etats, que l'unité de l'Europe ne se traduise, dans les domaines amont, par une régression irréversible. Il n'est pas encore trop tard pour réagir, mais on est tout de même bien près du point de rupture et de la dispersion d'équipes et de moyens résultant de longs investissements .

6. CONCLUSION (Pl. 17)

Je ne voudrais pas que cette alarme que j'ai cru devoir donner concernant les filières technologiques du futur occulte les très nombreuses raisons que l'on a de croire en l'avenir de l'industrie européenne de la Guerre Electronique. Cette Industrie dispose de réels points forts dans le domaine de l'intégration des systèmes. Elle a su créer une dynamique de coopérations et d'alliances fondée sur la volonté d'Hommes qui ont appris à se connaître et à s'apprécier. Elle peut faire

état de nombreux succès de par le monde, où elle s'affronte régulièrement dans des compétitions acharnées avec l'industrie américiane.

Les gens de ma génération avaient été, au début de leur carrière, très marqués par un livre paru en 1968 et ayant pour titre "Le défi américain" - Son auteur, M. Jean-Jacques SERVAN SCHREIBER y exposait entre autres très longuement combien les tous premiers Airbus allaient se voir dominés par leurs concurrents américains.

Trois décennies plus tard on peut faire le bilan de ce que peut réaliser l'Industrie européenne unie soutenue par une volonté politique forte.

Aujourd'hui, par ses concentrations massives, par son agressivité sur tous les marchés, l'Industrie américaine lance à l'Industrie européenne de la guerre électronique un formidable défi.

A nous, Industriels européens de l'électronique de relever ce défi et de prouver que ce que d'autres ont su faire dans le domaine des avions civils, nous savons aussi le faire dans notre domaine.

Trends in airborne electronic warfare : a European perspective

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1. ABSTRAT

Electronic warfare is one of the areas in which each major nation has tried to stay largely independent. As the European construction programme continues and budgets shrink, it would be reasonable to assume that this situation is now going to change quite quickly. In any case, the industry must be prepared for this scenario, even if the decisions are basically political.

The first point examined in this paper is that electronic warfare should be considered as a whole. It should no longer be approached on a programme-by-programme basis, or just in terms of equipment. On the contrary, our vision of electronic warfare should encompass intelligence gathering (to define the threats), technico-operational simulation (to specify which systems and equipment are needed to deal with the threats), evaluation, tests and life cycle support. And our approach to electronic warfare should also include all the spectral components of known or predictable threats.

A second consideration is that electronic warfare can no longer be dealt with as a separate area of interest. This is partly because of cost constraints, but partly because of the specific technical problems involved in co-siting different systems on board an aircraft. It is becoming more and more vital to make different systems share technical functions, apertures and time slots.

Current developments in modular integrated avionics are moving in this direction. Further efforts are needed in the field of sensors and antennas.

The third consideration discussed here is primarily of concern to our industry, but it cannot leave governments indifferent, as what is at stake is Europe's independence. I am talking here of the vital importance of maintaining European capacity in key technologies for which commercial applications cannot yet generate sufficient volume or which have cycle times that are incompatible with military programmes.

2. INTRODUCTION

There are three basic messages that I would like to illustrate in this short paper. All three messages actually say the same thing: we in the European electronic warfare industry are combining our efforts to propose the Alliance a European alternative to what American industry is offering.

First message (overhead 1): Electronic warfare has changed. It should be regarded as a whole, including everything from intelligence gathering to the deployment of countermeasures. Europe has some real strengths in this field, as well as weaknesses which it can overcome if we all pull in the same direction.

Second message (overhead 2): System costs must come down. Standardising modules, having them perform several functions, and seeking lower unit costs through higher volumes are steps in this direction. The European dimension already exists in this respect, and it needs to be pursued and expanded.

Third message (overhead 3): Electronic warfare uses specific technologies. Europe today has a good grasp of these key technologies, and we need not only to maintain our level of technology expertise but also to address new, promising fields that are opening up. Failure to do this may be one of Europe's biggest weaknesses, but it is not too late to react.

3. ELECTRONIC WARFARE HAS CHANGED

3.1 Recent shifts (overhead 4)

Without retracing the whole recent history of electronic warfare, suffice it to say that we have gradually moved from a notion of distinct items of equipment - radar warning receivers, jammers, and so on, each relying on their own technologies, and often added on during the aircraft life cycle - to a notion of integrated systems with non-dedicated technical functions, systems that can simply be reprogrammed for different missions and are part of the initial design brief of the aircraft.

The radar warning receiver provides an illustration of what I just called a non-dedicated technical function. This type of receiver has progressively had to match the level of sensitivity, selectivity and measurement precision provided by ELINT analysers and now relies to some extent on the same technologies. Another example is antennas built with active TR modules, which can be used for both detection and jamming functions.

3.2 Airborne electronic warfare: towards a system of systems (overhead 5)

At the same time, the traditional distinction between CW/meter-wave communications and pulse/centimetre-wave radar emissions has disappeared. The importance of having prior knowledge of the characteristics of the threat to be detected and identified has been demonstrated, the result being that the process of gathering the intelligence, programming the equipment libraries before the mission and analysing the data collected during the mission has become shorter and shorter.

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Also at the same time, with the emergence of multi-sensor systems, the optronic component has been added to the more traditional panoply of radar-based electronic warfare solutions.

What we need to design now, therefore, are global electronic warfare systems - or what I prefer to call systems of systems. These systems need to be based on our knowledge of the threat environment (the adversary's air defence and air-to-air weapon systems), the missions that need to be flown, and the RF environments encountered on those missions, to program self-protection systems or neutralise enemy air defences and then analyse the data brought back from the missions.

To do this, we need powerful means of technico-operational simulation, intelligence gathering, mission preparation and mission data analysis. For example, this operational simulation system called **SPARTE** (overhead 6) is used to simulate how self-protection suites react when an aircraft flies into an zone defended by a variety of weapon systems.

We also need highly specific solutions to help us design, integrate and then characterise these systems. (overhead 7)

The **SARGASSES** simulator, for example, is used to evaluate the radiation patterns of onboard antennas (reflection, diffraction, etc.), while the **MENGAM** test platform enables us to measure this radiation on a real aircraft. And the anechoic chamber at **BRETIGNY** is used for dynamic evaluation of systems in multiple threat environments.

3.3 One of Europe's strengths: integrated systems (overhead 8)

One point that should be stressed in particular is the effort that has been made in Europe in the field of integrated self-protection suites. We have largely succeeded not only in making the detection and jamming functions compatible with each other and in minimising equipment redundancy, but also, and most importantly, in making these functions compatible with other aircraft functions, such as radar and CNI.

The Spectra self-protection system for the Rafale combat aircraft is a good illustration of an integrated system in this sense, and equivalent examples could be cited for Eurofighter, Mirage 2000 and Tornado, and for the Tiger and NH 90 helicopters.

3.4 Two of Europe's shortcomings (overhead 9)

Although Europe now has a broad array of solutions for dealing with complex electronic warfare systems, we do have some weaknesses.

For example, in the field of electronic intelligence, the space component is still rudimentary. And yet space-based systems are the only way of gaining access to any region on the earth's surface on a permanent basis.

Another of Europe's shortcomings is in the area of jamming. A great deal of progress may have been made in aircraft self-protection suites, but escort or stand-off jammers designed to neutralise search and target designation radars are still missing from the European line-up. And yet this type of equipment has been used intensively by the American forces during recent conflicts, to the benefit of all the allied forces.

In both these examples, the basic techniques - electronic scanning antennas, digital radiofrequency memories, and so on - are available in Europe, and the financial burden is certainly not too heavy for a united Europe to bear, even if any single nation would find it hard to foot the bill alone. Developing systems like these would cost about one-tenth of any of the major programmes that are currently under way.

The needs clearly exist, and the techniques are available. So it is up to us in European industry to show we can set up transnational structures that are capable of defining a system, matching it to operational requirements, tailoring the costs to the budgetary environment and then implementing the programmes that are ultimately launched.

4. COSTS MUST COME DOWN (overhead 10)

On the subject of costs, there is now a clear consensus within Europe and within the Alliance at large, and everybody is demanding the same thing.

So what can European industry propose to meet these demands ?

4.1 Volume effects

One initial approach is to seek out ways of benefiting from volume effects during the production phase, which clearly means that requirements must converge.

The first place to look for these volume effects - as has already been said on many occasions - is in commercial or dual-use applications. This would have undeniable advantages in terms of initial supply costs, but there are also some serious difficulties connected with cycle times. Life cycles of commercial products are typically between 3 and 5 years, while military products have life cycles of 15 to 20 years.

This problem has nonetheless been overcome in standard components and the vast majority of digital components (processors and memories). Studies have determined to what extent the plastic packagings used in commercial products could replace ceramic packagings, and the results have been highly positive for certain packaging processes.

But this does not solve anything like all the problems encountered in electronic warfare, with special needs like very wide band microwave components, signal separation over very broad dynamic ranges, and very fast reaction times. And even if components often account for a critical proportion of the overall equipment cost - 40 to 50% - they are only one aspect of the problem.

To take our cost reduction efforts further, we need to act on the system architectures and set ourselves objectives such as using standardised, multi-programme modules and sharing resources among various different functions.

4.2 Modular integrated avionics: the European approach (overhead 11)

A first step has been taken in the digital processing sphere through the Modular Integrated Avionics approach, which

has been applied on the F-22 programme and has been adopted in Europe by Germany, the United Kingdom and France in their work on the Allied Standard Avionics Architecture Council (ASAAC).

Now, after a first phase of work conducted with the United States, these three countries have agreed to launch a common work programme. Over the next five years, this programme will permit to define and experimentally validate digital signal and data processing standards for combat aircraft. In contrast to similar American programmes - Pave Pillar, then Pave Pace - the European programme is laying particular emphasis on the use of COTS components (commercial off-the-shelf). The objective is to accommodate new hardware and software technologies that become available on the market without reversing earlier achievements, particularly operational software that has already been validated on the ground or in flight.

This programme is due to be launched mid-year and has led to numerous exchanges between the administrations and industries in the three countries involved and a consensus has now been reached as to the work that needs to be done.

4.3 Combining efforts: another example (overhead 12)

This European project is not the only one of its kind. The same desire to share research and development costs and benefit from volume effects was behind the decision by the same three countries to launch AMSAR, the joint programme focusing on active array antennas for onboard radars.

This graph illustrates the volume effect being sought through this approach. Here we have plotted the cost per TR module against the rate of production on a log/log scale, and we can see that the cost per module would fall by a factor of 2.5 for every tenfold increase in production volumes.

The main reason for this sharp fall in unit costs is that the modules will only deliver the requisite microwave performance if manufacturing is highly automated. A large proportion of the costs of producing the modules comes from amortising and maintaining the production plant, rather than from labour costs for recurrent operations.

This illustration shows that for a phased array antenna with a thousand TR modules to be cost-competitive with a more conventional solution using tubes and lenses, at least 6 to 8 radars or aircraft would need to be produced per month. This clearly does not correspond to the requirements of any single nation.

This example is a clear indication of the advantage of making the different types of modules needed for the different applications converge on the same production technologies and production systems. This approach is being adopted already, in particular by Elettronica of Italy and Thomson-CSF, as a way of bringing down the cost of electronic warfare modules for the self-protection suites of Rafale and Eurofighter.

Similar considerations lay behind the decision by the Thomson-CSF and Daimler-Benz groups to set up a joint subsidiary, called UMS, to handle their gallium arsenide foundry activities. It is probable that, as soon as production volumes are high enough, the groups involved will take similar moves to combine the manufacturing and test lines for TR modules.

The two examples I have just mentioned - modular integrated avionics and TR modules for active array antennas - go well beyond the scope of electronic warfare. But the same principles are equally applicable to the electronic warfare field and the reason I have used these examples is that they show quite clearly that European governments and industries are ready and willing to combine their strengths to rise to the challenges facing them.

4.4 Other prospects (overhead 13)

This kind of convergence at the production end of the process is not enough. To bring down costs effectively, we will have to take the principle of shared functions even further.

This is particularly true for microwave sensors, whose antennas account for a significant proportion of overall system costs, as well as posing a number of installation problems.

Europe is quite capable of adopting the same shared apertures approach as the United States, where the same antenna or radiating surface is used for radar, electronic warfare and CNI functions. Partly because of the need for the different functions to share time on the apertures, this approach calls for detailed exchanges about the exact way each system works. This is not yet the norm in the electronic warfare field, but it will become indispensable if we want to pursue our cost reduction efforts. The major industrial groups are quite prepared to do this.

5. CONTROLLING THE TECHNOLOGICAL PLATFORM

Even if electronic warfare will have to rely increasingly on standardised modular functions in the future - as I indicated earlier with the examples about digital processing and antennas - there is no doubt that increasingly specific requirements will continue to make it essential to find innovative technological solutions.

5.1 Specific needs of electronic warfare: examples (overhead 14)

I have already mentioned three of these specific requirements:

- frequency coverage extending from decametre wave (for anti-stealth radars) to millimetre wave,
- high selectivity combined with wide instantaneous bandwidth to detect increasingly discreet and agile radars in a broad range of frequencies,
- reaction times measured in nanoseconds.

So far, Europe has managed to maintain an adequate technological platform to meet the specific requirements of electronic warfare.

5.2 Europe's technological platform (overhead 15)

I would like to give three important examples of how Europe has so far managed to keep control of its technological platform.

5.2.1 Electron tubes, and travelling-wave tubes in particular, which are still commonly used in radar jammers: This is a good example of an area in which defence research and non-defence research have combined to bring Europe first-rate design and production resources. (Thomson-CSF, including the electron tubes activities formerly conducted by AEG, ABB and Siemens, is world leader in this area.) The contribution that electronic warfare has made to this performance should be mentioned here. To meet the specific needs of electronic warfare applications, researchers devised more robust tubes that provided useful safety margins in less critical applications.

5.2.2 Surface acoustic wave filters, which are used in channelised receivers (compressive receivers or filter bank channelisers) This is another good example of the commercial spin-offs of research initially undertaken for the defence community. Thomson Microsonics, the subsidiary Thomson-CSF set up to ensure a secure supply of surface acoustic wave filters, now produces 90% of its filters for commercial markets such as cellular telephones and medical probes.

5.2.3 Gallium arsenide : The specific requirements of electronic warfare (including low-level amplification in millimetre wave or wideband power applications) have driven a number of other developments that should also find large numbers of applications, although this is taking longer to happen that had once been hoped.

A non-unified Europe has so far managed to develop an adequate technological platform, and as these examples show, the results are undeniably state of the art at a worldwide level.

Paradoxically, with greater unity on the horizon, Europe seems undecided about consolidating the progress made earlier by individual countries.

5.3 New technologies to harness (overhead 16)

New requirements are emerging in the electronic warfare arena, and there is every chance that new technologies will be used to satisfy them. Here again, I would like to mention three examples.

5.3.1 Microwave filtering: Interfering signals, which are becoming more and more numerous, need to be removed as far upstream as possible in the reception chain. ***Superconductive filters*** offer an effective response to this requirement, but little has been done in Europe beyond laboratory demonstrations.

5.3.2 Power amplification at low frequencies: This problem is not specific to electronic warfare, but multi-octave amplifiers with very high performance are needed to jam telecommunications and search radars operating at broader and broader bandwidths. ***Silicon carbide*** technology is a solution to this problem and also offers a good deal of potential for detecting missiles by their ultraviolet signatures. But here again, little more than preliminary demonstration has been conducted in Europe.

5.3.3 Ultra-fast signal processing: Multiplexing antenna outputs, storing signals either for detailed analysis or for retransmission after alteration, and remoting those same signals, will be more and more clearly defined requirements of future electronic warfare systems. Optronic devices offers some satisfactory solutions to these requirements, and a number of applications already exist, such as microwave transmissions over optical fibre. But a great deal still remains to be done in this area.

These are three examples of requirements for which technological development paths and competencies already exist. But, unlike the United States, Europe is still hesitating, and it is justifying its hesitation for questionable reasons.

One of these reasons is that "programmes" will need to finance these developments to show that they serve some useful purpose. This attitude overlooks the fact that it will take 5 to 10 years to master these new processes and that no programme can run the risk of relying on technologies that are not yet proven.

Another reason put forward is that industries should assume responsibility for developing the technologies they will need for their future products. This overlooks the fact that companies today are judged on the basis of their short-term results. Trying to demonstrate that a new technology will be economically viable 5 to 10 years hence is more than a little risky in these new areas.

And yet, as the examples I gave earlier showed, it was military requirements that drove the development of new technologies that now have interesting commercial spin-offs - and not the reverse. And this will continue to be particularly true in the electronic warfare sector.

It is in areas like this that governments need to support the initial efforts. This used to be well understood by European countries and is still the order of the day in the United States. Let us hope - and here I am speaking more particularly to representatives of governments - that European unity will not translate into irreversible regression in upstream research and development regarding military needs. It is not too late to react, but we are nonetheless coming close to the breaking point, the point where the teams and resources we have invested in for so long are just thrown to the winds and lost forever.

6. CONCLUSION (overhead 17)

Although I do feel duty bound to raise the alarm about Europe's attitude on future technologies, I would not like that concern to conceal the many reasons we have to believe in the future of the European electronic warfare industry. This industry has some real strengths in the field of system integration. It has succeeded in building up some a real momentum in terms of partnerships and alliances, based on the determination of men and women who have learned to know and appreciate each other. This is, after all, an industry with a remarkable record of success and achievement in many parts of the world, in markets where it has grown accustomed to the relentless battle with American competitors.

Many people in my generation were deeply affected by a book by Jean-Jacques Servan Schreiber published in 1967 called *Le Défi Américain* (The American Challenge). This book included a lengthy treatise on how the airliners that Airbus was starting to produce were going to be completely dominated by their American competitors.

Thirty years on, we can look back at what a unified European industry can do when it has the political will behind it to succeed.

Today, through massive consolidations and concentrations and aggressive marketing throughout the world, American industry is setting an enormous challenge to the European electronic warfare industry.

It is up to us in the European electronics industries to rise to this challenge and to prove that we, in our own area of specialisation, can do what others have done in civil aviation.

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AIRBORNE ELECTRONIC WARFARE TRENDS

A EUROPEAN PERSPECTIVE

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Trends in Airborne E.W.

A EUROPEAN PERSPECTIVE

FIRST MESSAGE

- E.W. has to be regarded as a whole

  From intelligence gathering ....
  .... to countermeasures deployment

  - Europe has real strenghts in this fleds

    But also some weaknesses which it can overcome

Trends in Airborne E.W.

A EUROPEAN PERSPECTIVE

SECOND MESSAGE

- COST REDUCTION is a MUST

  VOLUME EFFECTS offer a response
  and also new SYSTEM ARCHITECTURES

  - EUROPEAN INITIATIVES are now running

    Their field has to be extended

Trends in Airborne E.W.

A EUROPEANPERSPECTIVE

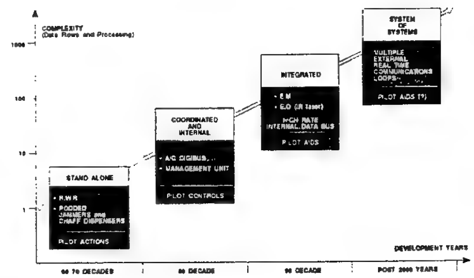
THIRD MESSAGE

- E.W. uses SPECIFIC THECHNOLOGIES

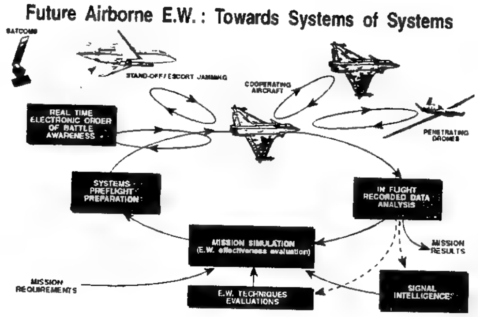
  - Europe today MASTERS the present KEY TECHNOLOGIES

    - Europe has now to adress NEW PROMISING FIELDS

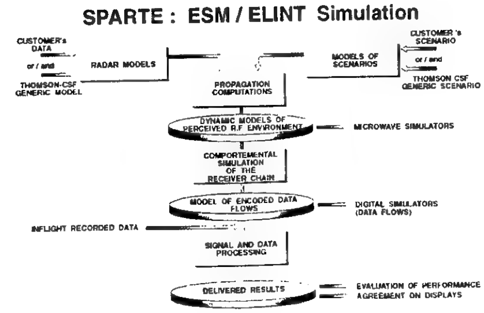
Airborne E.W. Evolution



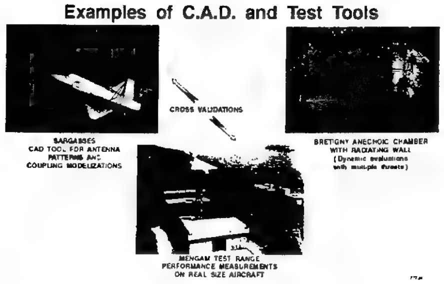
Future Airborne E.W. : Towards Systems of Systems



SPARTE : ESM / ELINT Simulation



Examples of C.A.D. and Test Tools



Trends in Airborne E.W.

ALLIED STANDARD AVIONICS ARCHITECTURE COUNCIL

<u>PHASE 1</u> (Fr - Ge - UK - US)

- Architecture concepts : (Software - Network - Common functional Modules - Packaging) for signal and data processing

Completed Feb. 1994

<u>PHASE 2</u> (Fr - Ge - UK)

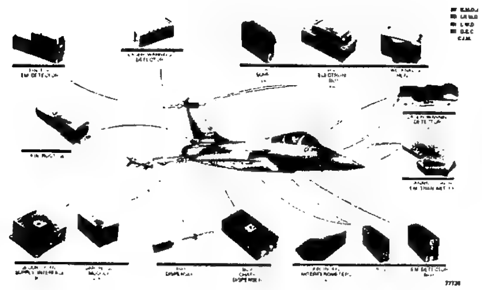
- Concepts refinement
- Core processing - Sub System - System demonstrations

Planned Kick-off : mid 97

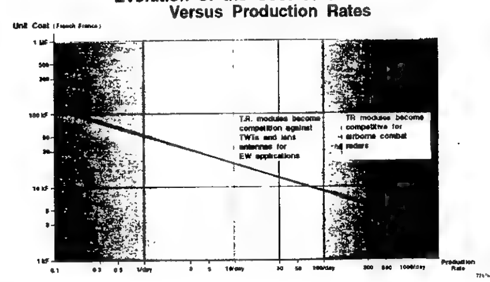
FOCUSED ON COTS

A MAJOR INTEREST FOR E.W. - APPLICATIONS

SPECTRA



Evolution of the Cost of T.R Modules Versus Production Rates



Trends in Airborne E.W.

TWO EUROPE'S SHORTCOMINGS

SPACEBORNE SIGINT

- ACCES TO ANY REGION ON THE EARTH'S SURFACE
- PERMANENCY

Proven airborne techniques could easily be transferred on satellites

ESCORT / STAND OFF JAMMING

- ONE MEGAWATTS EFFECTIVE RADIATED POWER NOW REACHABLE ON AIRBORNE PLATFORMS WITH ELECTRONIC SCANNING ARRAYS
- EFFECTIVE JAMMING AGAINST HIGHLY PROTECTED RADARS NOW POSSIBLE WITH DIGITAL RADIOFREQUENCY MEMORIES

COST CLASSES BETWEEN 1 to 3 GF following performances

Trends in Airborne E.W.

TOWARDS SHARED APERTURES

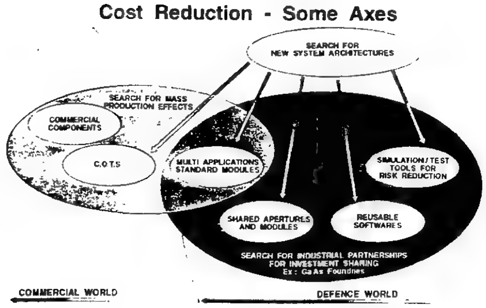
MAIN OBJECTIVES

- E.W., CNI and RADAR functions
- 4 π steredians coverage
- Full frequency coverage (100 MHz - 40 GHz)
- Dual polarization / Flush mounting / low R.C.S.

TWO TRACKS

- High frequencies (> 2 GHz) : Solid State Arrays
- Low frequencies : Conformed printed spirals

Cost Reduction - Some Axes



Trends in Airborne E.W.

SOME E.W. SPECIFIC DEMANDS

- **ULTRA WIDE FREQUENCY SPECTRUM COVERAGE**
  from the V.H.F. to the mmWaves (100 MHz - 40 GHz)
- **HIGH SELECTIVITIES ALLIED WITH WIDE INSTANTANEOUS BANDWIDTH**
  100 kHz resolutions with 0,5 to 2 GHz bandwidth
  and
  60 to 80 dB dynamic ranges
- **FAST REACTION TIME**
  Now a few nanoseconds

Trends in Airborne E.W.

EUROPE'S TECHNOLOGICAL PLATFORM : 3 EXAMPLES

- **TRAVELLING WAVES TUBES**
  Now with commercial support (Telecom, Medical ...)

- **ACOUSTIC WAVES DEVICES**
  Now with commercial support (Cellular Telephone, Medical)

- **GALLIUM ARSENIDE FOUNDRIES**
  Specific Foundries (Power Mesfet or HBT or mmW - 0,15 µ)
  not yet supported by commercial applications

Trends in Airborne E.W.

NEW REQUIREMENTS AND NEW TECHNOLOGIES EXAMPLES

- **MICROWAVE FILTERING**
  ====> SUPERCONDUCTIVE FILTERS

- **POWER AMPLIFICATION AT LOW FREQUENCIES**
  ====> SILICON CARBIDE

- **ULTRA FAST SIGNAL PROCESSING**
  ====> OPTRONIC DEVICES

Trends in Airborne E.W.

CONCLUSION

- **REAL STRENGTHS OF THE EUROPEAN ELECTRONIC WARFARE INDUSTRY**
  Well illustrated in the field of SYSTEM INTEGRATION

- **A REAL MOMENTUM IN TERMS OF PARTNERSHIPS AND ALLIANCES**
  Well illustrated by the ASAAC and AMSAR initiatives

- **DETERMINATION OF MEN AND WOMEN KNOWING AND APPRECIATING EACH OTHER TO COPE WITH THE AMERICAN CHALLENGE AND TO PROVE THAT THEY CAN DO WHAT OTHERS HAVE DONE IN CIVIL AVIATION**

Future Trends in Image Processing and Pattern Recognition

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Summary

The strong evolution of the scientific background and of the imaging technology is transforming image processing in a discipline where the boundaries between the sensor system, the processing system and the visualization and/or decision making system are vanishing. Indeed, it is more and more difficult to split the design of signal processing algorithms from the design of pattern recognition algorithms or the preprocessing dedicated to the sensor system from the decision making process.

Sensor systems are also evolving very fast, their variety increases and their resolution is getting better in all domains (temporal, spatial and wavelength domains). Therefore, they are one of the fundamental reasons for the modern evolution in processing algorithms and hardware design, especially in data fusion and parallel processing.

The design of modern pattern recognition systems, that show an *intelligent* behaviour, has to cope with the huge multiplicity of inputs at different levels. These inputs must be combined and fused in order to extract the useful information and to make possible the decision making.

Finally, the computer hardware performance and integration fortunately still increase exponentially so that it still remains possible to implement the more and more sophisticated, real-time or near real-time applications on existing hardware.

1 Introduction

In the early development of image processing methodologies, a clear boundary was existing between the matters considering the images as signals and the matters considering the images as documents which can be understood predominantly by the brain [Rosenfeld, 1982]. The former ones include all the methods related to image restoration, enhancement, compression, interpolation, etc. The latter concern all the pattern recognition methods, including as well the low level operations as the high level ones dedicated to reasoning activities.

Nowadays, this frontier between these two disciplines of image processing is vanishing. As a matter of fact, signal processing algorithms are mixed with pattern recognition methods in a lot of image processing applications. For instance, in image compression, a very high compression ratio can be achieved after segmenting the images with respect to different types of features

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like colour, texture, edges, etc., and by coding separately the contour information and the segment content. Similar approaches are used in the field of adaptive image restoration.

In the same order of ideas, signal processing algorithms are actually used in pattern recognition applications as direct or indirect means to extract features. So, sophisticated filters with specific local and spatial properties are used to extract specific objects/targets in the images; multi-resolution approaches based namely on the wavelet transform are used to perform specific pattern recognition tasks at the different resolution levels.

A next evolving and emerging characteristic of image processing is the nowadays accelerated development of the sensor technology. The new instruments are covering several times the spectral region covered by the human eye and are able to provide new understanding of the world around us [Breckinridge, 1997].

Since, the number of sensors which can be used to observe a scene is still increasing (X-rays, visible, near infrared, far infrared, mm waves radiometers, synthetic aperture Radar, etc) it is important to manage and organize the resulting huge amount of data available. Gathering essential information from several types of sensors is getting a crucial problem in situation assessment and decision making (e.g. the humanitarian and the military mine clearance problems). Accordingly, the data fusion techniques are evolving very rapidly. Based on the assumption that the a posteriori probability of detection, recognition and identification increases drastically in a multi-sensor environment, efficient data fusion methods should be developed, from the lowest level (pixel level) to the highest level (decision making level). More specifically, the lowest level methods imply the direct use of image processing algorithms and eventually derived 3-D information (e.g. Digital Elevation Model - DEM from stereo pairs) in order to register different images provided by different sensors. On the other hand, high level data fusion techniques are indirectly involving image processing algorithms by combining and integrating them in a high level reasoning architecture (e.g. a probabilistic blackboard model). Solutions are emerging, containing low and high level methods, production systems where the sensors and the reasoning entities are integrated.

Another important artefact of the accelerated development of the sensor technology resides in the rapid increase of the sensor resolution (e.g. the resolution of the remote sensing satellites has increased by a factor much larger than hundred in ten years). This phenomenon, which is far from being stopped, together with the increasing complexity of the processing methods, addresses the problem of the computing power, the amount of memory and the storage capacity and will certainly still have a large impact on the computer architectures particularly if real-time applications are concerned.

2 Signal processing and pattern recognition merging

A well-known application of signal processing methods in image processing is image restoration. Mostly, it aims at removing blur in presence of observation noise. The inversion problem being ill-posed, regularisation procedures are commonly used to make the deblurring well-behaved. Many restoration methods have been proposed but most of these consider space-invariant restoration.

Adaptive restoration methods, that consist of computing an inversion filter depending on the local properties of the image have only recently been proposed. These methods often involve the use of local image descriptors based on functions with a local support like wavelets, windowed polynomials or Gabor functions.

Adaptivity is obtained by estimating local properties for the original image and by selecting an appropriate restoration filter. Often however, adaptive schemes consider the image as an isotropic two-dimensional signal, what is obviously not the case in the presence of edges. These adaptive schemes produce edge transitions which are sharpened but yield noisy edges. This can be solved by introducing directional adaptivity, i.e. by estimating local features in various directions, allowing to cope with the image anisotropies.

In order to achieve directional adaptivity, the images can be described using direction sensitive functions. Good candidate transforms are the short-time Fourier transform (STFT), Gabor transform [Neyt, 1996] and gradients [Korn, 1989].

By adapting the restoration filter according to

Figure 1: Detection of the vertical rectification pattern of a Meteosat 6 image, rectified with spline functions. The transition from one black strip to another one black strip corresponds to the displacement of one pixel vertically.

the local (both spatial and directional) signal characteristics (edged non-edged regions, flat or textured regions) an optimal restoration can be achieved.
Clearly, the detection of flat or textured regions and of edges by appropriate local descriptors could be done directly or indirectly by pattern recognition methods which could be integrated directly or indirectly into the restoration process in order to take into account of the intrinsic non stationarity of images.

An other example consists of the use of very narrow filters (e.g. from a Gabor filter bank) with directional properties to detected small coherent displacements in a selected direction. Fig. 1 shows an example of vertical rectification pattern detection in a satellite image [Neyt, 1996b].

In image compression, region oriented transform coding (ROTC) is an example of a method which takes into account the non stationarity of image signals, offering higher compression ratios than conventional block transform coding techniques (like JPEG).
In the ROTC methods, the image is partitioned into a number of regions, which can have arbitrary shapes and in which the image intensity varies slowly. The intensity distribution in each region is approximated by a weighted sum of a small number of base functions (e.g. orthogonal polynomials).
Moreover, the segmentation methods that are used to delineate the regions play an important role in the result of the image compression and reconstruction. Therefore, effective and fast segmentation methods are required. Here also, so-called pattern recognition methods must be used to segment the images and must be integrated in a global signal processing algorithm [Philips, 1994].

In the same order of ideas, it is well known that the neural net architectures are used in a lot of pattern recognition applications, namely as classifiers or probability estimators. The same types of architectures can also be use in signal processing applications, namely to compute an adaptive wavelet transform or a restoration filter [Mangen, 1995].

Also in the case of pattern recognition applications, signal processing methods are often involved. For instance, satellite images represent a huge amount of information and a multi-resolution approach enables to have this information available in a pyramidal structure thus providing a hierarchical processing to obtain this information. Concerning this point, see also further in paragraph (4.1) the multi-resolution approach of low level fusion. For automatic georeferencing satellite images, reference points must be detected and matched with geographical information stored in a data base and the detection algorithms depend on the sensor and on the image resolution. The first coarse positioning of these reference points can be performed on the low resolution version of the images in order to reduce the search space, a finer positioning can be achieved afterwards, by using the higher resolution versions of the same images. In this case, the so-called hierarchical matching process can be performed after computing a multi-resolution version of the image (using e.g. the wavelet transform, the multi-scale DCT, etc). Moreover, the high spatial frequency images (the difference images) provide an edge image which can also be used for edge detection purposes. Clearly, this implies the use of signal processing methods to compute pattern recognition search and detection algorithms.

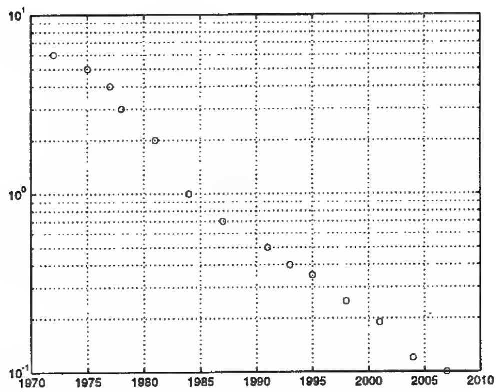

Figure 2: Evolution of the minimum feature size (in μm) in the semi-conductor technology

3 Sensor technology

The reduction of the minimum feature size in the semiconductor technology (from 6 μm in the year 1972 to 0.25 μm in 1997 and 0.1 μm expected in 2000) plays an important role for the development of high resolution sensor system and the increasing computer complexity.

For example, in the last twenty-five years, the number of pixels on a CCD-image sensor increased from thousand in 1972 to approximately 60 million in 1996, and CCD-image sensors with 15k×21k pixels can be in principle realized today.

Moreover, a large variety of sensors has been and will be further developed :

- in the category of the electro-optical sensors, we find in the first line the CCD-image sensors, the multi-spectral/hyper-spectral sensors, the low-light television, the UV-solar blind and the FLIR (forward looking infrared);
- in the category of the Radar systems, we find in the first line the well known synthethic aperture Radar (SAR), the interferometric Radar, the Radar real aperture/MTI (moving target indicator), the surface penetrating Radar and the mm-wave radiometer;
- the laser Radar (LADAR).

In an operational context, it is particularly important for targeting and surveillance mission that all these sensors could operate from a large variety of platforms. In this context, a future multi-sensor environment should consist of at least

- MIR (medium infrared - 3-5 μm or 10-12 μm)
- VIS (visible)
- SAR, Interferometric Radar
- MIT

All with fixed registrations and calibrated outputs.

From the above considerations, it results that a lot of efforts must be devoted to the development of effective parallel computing platforms because of the huge and dramatically increasing amount of data to be processed and that effective software must be developed to take into account the multi-spectral data produced by a variety of sensor systems and the extraction of useful information from the terabytes of data available.

4 Pattern recognition applications in a multi-spectral context

A direct consequence of the development of multi-spectral sensors is that the information picked up by the sensors must be combined or fused in some manner in order to get an optimal influence on the decision making process by optimizing the object/target acquisition. Several methods can be distinguished in order to fuse the information, from the lowest to the highest level. Three different forms of information fusion are commonly reported : the low level fusion methods merge the information at the data level, the intermediate fusion techniques combine the information produced by features extracted from the data and, in the high level fusion, the data are fully processed independently and the merging is done at the decision level.

To perform the fusion, features must be extracted from different sensors at a same location. Therefore, the images should be registered, geolocated

or collocated. Geocoding and collocation are often preferred in order to avoid resampling distortions.

The following sections are far from being exhaustive and are only intended to give some insight on emerging topics.

4.1 Low-level fusion

When the different sensors have compatible data rates, data dimensionality, and formats, it is possible to fuse the raw data from the different sensors at the front end of the processing stream, immediately after acquisition.

In this approach, the set of data (images) from different sensors are combined into a single image taking into account all the relevant information picked up by the different sensors. Low-level fusion is therefore useful to enhance fine details in the data that might otherwise be lost by the subsequent processing steps. Methods for such multi-dimensional fusion are well established. Principal components analysis (PCA) methods (such as the Karhunen-Loève transform) or frequency domain methods (based on wavelets or Gabor transforms) are frequently applied.

For this purpose, multi-resolution low level fusion of different spectral bands is an interesting approach. The data fusion (collocation) of data taken at different resolutions in different spectral domains consists of the determination of the set of pixels from a given channel with high resolution that are covered by a given pixel of a channel with lower resolution. This collocation procedure allows a sub-pixel analysis of the low resolution data channels with radiation data observed at high resolution. It requires the knowledge of the technical characteristics (i.e. the point spread function) of the different sensors. The collocation of data for the purpose of object/target detection is of particular interest if the spectral band of a given low resolution channels covers the spectral band of a high resolution channel. In the latter case, the spectral response of the low resolution "broad band" channel gives the relative contribution of a given "small band" radiance observed at higher resolution to the "broad band" radiance observed at low resolution. The merging of radiation data observed at different scales may be, therefore, an important contribution to enhanced object/target identification in multi-spectral data observed at different scales. Implicitely, the latter way of doing consists of applying a signal processing solution to a pattern recogniton problem.

However, the quality of the registration of the data from different sensors is often critical. Low-level fusion will have an adverse effect on overall performance of a target detection system if the data to be fused are not properly (pixel-wise) registered. Generally, constraints must be fulfilled in order to register data in a best way. Namely, a digital elevation model (DEM) must be known or at least it should be possible to derive it from the data; the data and the DEM should be compatible with respect to the resolution or otherwise they should be adapted in order to get dimensionally superimposable images; the sensor characteristics and the recording conditions should be known.

The low-level fusion algorithms are producing fused data ready to be interpreted by a higher level, but are not yielding results at the decision making level.

4.2 Intermediate level fusion

A feature extraction phase and a segmentation phase are often required processing steps for the higher level fusion before the decision making process.

Feature extraction and segmentation

Depending on the sensor and the object/target type, the appearance of the objects/targets of interest will vary (e.g. for a given low resolution channel, the sought objects/targets will appear as white or black spots, the same objects/targets could appear as textured areas on high resolution visible images or as homogeneous areas on high resolution IR images). To select the relevant features, physical models of image acquisition systems and/or model images (e.g. out of a database) should first be analysed. The selected features should then be used as an input for a segmentation process which can be supervised (making use of classifiers optimised with a training data set during a learning phase) or unsupervised (segmentation and classification in regions taking into account the actual discrepancies of the features values from pixel to pixel).

Some examples of unsupervised feature extraction methods are given below.

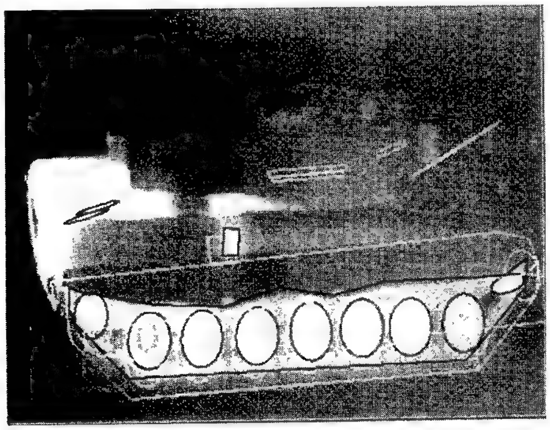

Figure 3: Example of supervised feature extraction on an IR tank image

Isolated white or black regions as they could appear in low resolution images, can be detected by computing a local minima (maxima) detection followed by a region growing method.

An important number of methods are available to segment homogeneous regions, e.g. watershed based on the gradient or on a distance map, region growing, contour based threshold voting, etc.

Texture measurements (e.g. Haralick parameters, the wavelet coefficients, ...) can be computed to detect textured objects/targets. Those texture measurements provide a multi-dimensional description of the image, involving multidimensional segmentation methods (e.g. region growing, Principal Components Analysis (PCA) or clustering).

Feature level fusion

In a so-called feature level fusion process, candidate features for object/target presence detection are extracted from the data of each sensor and pixelwise accumulated into a super-set of features. If a supervised approach is appropriate, test images can be used for which the object/target true position is known. Then the most discriminating features can be selected and optimally combined by using statistical methods. The output of this type of feature level fusion is a new set of features.

Feature level fusion can also be done by converting the features extracted from the different images into a probabilty that an object/target is present. Such a supervised feature fusion can be performed by means of an MLP (Multi Layer

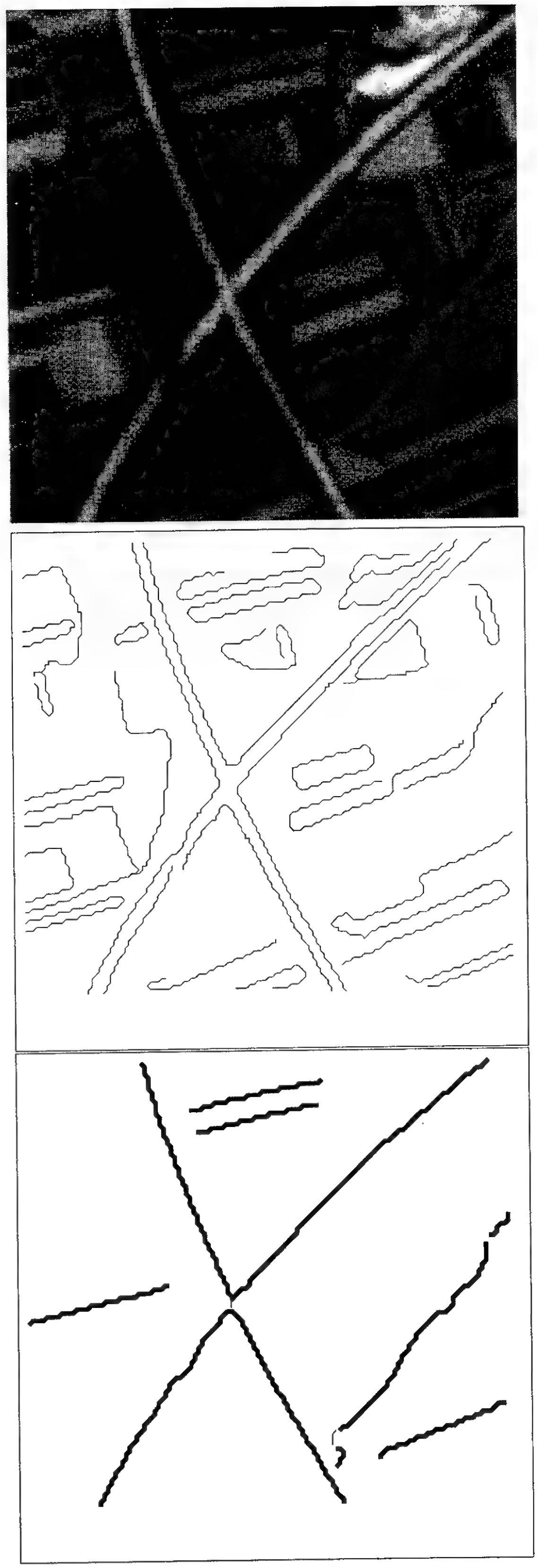

Figure 4: Example of feature extraction for road detection on a SPOT image [Lacroix, 1996]

Perceptron). The inputs are the features extracted from the different sensors at a given location and the output will be the probability that an object/target is present. A confidence map is thus produced. This map should be segmented to provide the shape of individual objects/targets and a global confidence (mean confidence on the segment, ...) for that object/target. The shape of the object/target candidate can then be used to influence the global confidence on the object/target presence.

4.3 High level fusion

If a combination of sensors with different characteristics is used when performing object/target detection it may be useful to apply feature extraction methods to the original images and then fuse the resulting features in an "intelligent" way.

In order to achieve this the knowledge of a human operator could normally be applied when combining the results of the feature extraction algorithms. Based on his experience and on physical rules, as well as the order in which he applies the different algorithms to the images, these procedures must be incorporated in the global (semi-)automatic object/target detection system.

One of the problem solving methods which is particularly well suited for this type of problem is the blackboard model. It consists of a central shared memory and a set of independent knowledge sources, communicating solely through the central blackboard. The solution is built incrementally starting with a partial hypothesis which is expanded gradually with contributions of the different knowledge sources [Heinze, 1996].

For example, the following knowledge sources can be used:

- *global strategy (active vision):* a human operator would apply "*detectors*" to the different images in a specific order. The focus of his attention is not sweep from left to right and top to bottom in the different images but rather hop from region to region, based on the distribution of the density of detected features in the images. He may for instance locate regions with a lot of bright blobs in a channel image (e.g. Radar) and associate these with candidate objects/targets for which confirmation is then searched in other channel images (e.g. visual and IR images).

  In order to select the region of interest, the knowledge of specialists is useful. They can predict the possibility to find an object, taking into account the knowledge of the geographical situation and the knowledge of, military speaking, the tactical value of each region (e.g. bridges, railways, routes, ...).

- *generic rules:* The known designs of specific objects/targets allow a human expert to set up a set of generic rules, translating his knowledge with respect to the object/target's design, combined with his knowledge of the rules of physics, into constraints on the intensity or texture of regions in the different images.
  The generic rules can be represented using a fuzzy rule based expert system. This allows the human experts, who have to set up the rule base, to continue using the vague linguistic terms they typically use when explaining a reasoning, instead of having to choose sharp go/no go thresholds.

- *local detectors:* The local detectors extract features from the images or divide these in segments, based only on local image information in one single image. The local detectors are activated by other knowledge sources through entries on the blackboard. They may in this way pass parameters to the local detectors, such as a specific region in the image in which to search for a specific form. In this way a local detector can nevertheless indirectly use information from other spectral channels or other local detectors.

The three levels of fusion as well as combinations thereof can be used and their results compared in order to optimise the performance of an overall object/target detection system. Note that the above described method produces the confidence of object/target presence which can be very useful.

All the topics mentioned above are extremely important for future architectures of pattern recognition systems. A visionary view of such a system is illustrated in Fig. 5. The auto-

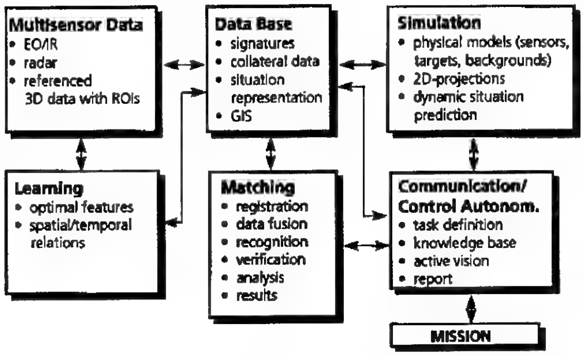

Figure 5: Visionary view of the architecture of an object/target acquisition system.

matic detection of Regions of Interest (ROI's) involves a large reduction of multisensor data. Using Geographical-Information-Systems (GIS) the classified objects/targets can be localized. They are taken as proposals which can be inserted automatically in a mission report. It is assumed that the role of the human image interpreter will change from an operator of a surveillance/reconnaissance system to a supervisor of automatically generated object/target acquisition results.

5 Computing power

The implementation of the intelligent processing of multi-spectral data would not be possible without increasing computer power. Fortunately, the computer hardware evolves at a comparable speed as the sensor technology and the software capabilities. The reduction of the minimum feature size in the semi-conductor technology has already been mentioned (paragraph (3)). This reduction is one of the fundamental reasons for the complexity increase of microprocessors in the last twenty-five years (from 2.300 transistors per micro-chip in 1971 to 5.500.000 transistors in 1995). The Moore's law is nearly always applicable : the performance of a micro-chip is doubling êvery two years (in fact, actually, every 18 months) and the performance of dedicated micro-electronics (ASICs) amounts actually to GigaFLOPS.

The architecture of the processing systems is also evolving. Nowadays, parallel architectures allow the parallel computation of connected or independent tasks. Often, the concept of central processing units is disappearing and a distributed architecture is currently preferred. This evolution is also relevant for pattern recognition applications where more and more intelligence is given toward the sensor system, by favouring distributed processing [R. Viswanathan, 1997].

6 Specificity of military pattern recognition

In military applications, pattern recognition is also a multi-facet field requiring multi-sensor technology, intelligent algorithms, hardware and software architectures.

Military systems must be able to operate very fast, safely and in a reliable way. They have to cope with hostile situations and often unstructured environments (demolitions, smoke, etc). Therefore, optimizing target acquisition and using appropriate harware is crucial to speed up operations and to increase as well the efficiency of operational decision making as the reliability and the safety of military actions. With this respect, we can conclude that the effects of the modern evolution of pattern recognition as described in this paper (multi-sensors, data fusion and optimized hardware architectures) are not only relevant for military applications, but are amplified.

Further, the combinatorial explosion of target signature variations and military relevant configurations for targeting tasks on land, sea or air due to acquisition parameters, target phenomenology (e.g. infrared thermal behaviour), or target/clutter interaction are more specific to military applications of pattern recognition although their fundamental tasks are similar to those of the other pattern recognition applications, that is pattern detection, classification and identification, using feature extraction and object description. Pattern detection, classification, and identification are here understood as being the verification of learned structures.

Finally, it is noted that invariance against a lot of transformations, robustness against missing or supplementary structures, and regard of dependencies on collateral data are extremely important for military applications.

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Real Time Specification of the Battle Space Environment and Its Effects on RF Military Systems

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1. SUMMARY

The critical nature of electromagnetic propagation assessment in the development of a wide range of sensor, communications and weapon systems is highlighted. A brief description of the Battle Space Environment, together with methods to specify it are given. A number of contemporary decision aids are used to illustrate both the importance of accurate, timely environmental specification, and of accurate ray-tracing, to NATO operations. The importance of using new sensors, data fusion and advanced computer assets is identified.

2. INTRODUCTION

NATO communications, radar and navigation systems rely on the propagation of electromagnetic (EM) waves and are affected by the environment through which those waves must propagate.

As an example, the troposphere (a non-ionized region of the atmosphere extending from the ground to ~10-15km) may cause signals, across a wide frequency range, to deviate from straight line paths and to be attenuated by rain, fog, and molecular absorption. Atmospheric refractive layers may also channel or duct electromagnetic energy very effectively. One persistent ducting mechanism found over oceans is the so-called evaporation duct. These various effects can be exploited for communications and surveillance far beyond the horizon but can also be a source of system performance degradation, such as the formation of holes in radar coverage.

The ionosphere, which extends from ~80 to ~1000 km, significantly affects the propagation of high frequency (HF) and ultrahigh frequency (UHF) signals. The effects are varied but include refraction, retardation and scintillation. HF communications and radar systems exploit some of these effects to advantage but other military systems are degraded. Positional errors in ballistic missile defence systems and loss of phase lock and range errors in GPS (Global Positioning System) are examples of such deleterious effects. Table 1 provides quantitative estimates of these effects.

If the environment was isotropic and stable in time, it would be relatively easy to determine its effects on the propagation of EM waves. Unfortunately, this is not the case. The spatial scales vary from thousands of kilometres to turbulence with scale sizes of a less than a metre. Likewise the temporal scales vary over many orders of magnitude from many years (solar cycle effects on ionospheric propagation) to hours or even minutes (the scale of weather phenomena).

As a consequence of this variability, timely and reliable strategies are required to both specify and accurately forecast the Battlespace Environment and to assess the attendant impact on the operational performance of military systems. These strategies can be used to automatically apply corrections to the system operating parameters or, via a decision aid, advise the user on a course of action which will improve the military functionality.

In this paper we will provide both a brief review of radio frequency (RF) propagation through the Battlespace Environment and, the specification of that environment. Further details on these topics can be found in the lecture notes associated with AGARD Lecture Series 196 on "Propagation Modelling and Decision Aids for Communications, Radar and Navigation Systems" [*AGARD*, 1994]. The applications of this research and technology are illustrated by descriptions of in-service decision aids. The paper concludes with an assessment of the way forward and the advances that we might expect in the next ten years or so.

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 2.

Table 1. The effects of the ionosphere on C3I systems

	Communications	Surveillance	Navigation	
Systems	HF communications UHF/SHF satcoms SKYNET AFSATCOM FLTSATCOM LEO cellular SATCOM telephones	UHF/SHF radars BMEWS , PAVE PAWS COBRA DANE HF OTHR radar ROTHR, OTH-B Spaced based SAR Geo-location	GPS TRANSIT	
Effects	Character errors Loss of comms	Range errors Loss of target discrimination	Range errors	Loss of phase lock and data loss
Severity	30 dB fades at UHF 20 dB fades at L-band	Over 200 m at UHF	Single freq position errors up to 75 metres	Loss of position update
Causes	Ionospheric irregularities	Electron content variations Irregularities	Total electron content	Irregularities

3. NATO PERSPECTIVE

The background to defence systems procurement and the application of those systems has changed radically over the past few years. The previous monolithic threat to NATO has changed to a wide spectrum of threats all of which needs to be addressed within a background of a reducing budget. The new NATO strategy requires improved flexibility, mobility and situational awareness. Technologically this requires better communications, navigation and, an improved remote sensing capability. In order to meet these requirements better specification of the effects of the Battlespace Environment is required.

4. TROPOSPHERIC RADIO PROPAGATION ASSESSMENT

Atmospheric refractive layers may channel or duct electromagnetic (EM) energy very effectively. One persistent ducting mechanism found over oceans is the so-called evaporation duct. It is caused by the rapid decrease of humidity above the water surface. Depending on frequency, evaporation ducting can enhance signals by many orders of magnitude for over-the-horizon propagation. Timely and reliable assessments of evaporation ducting effects are crucial for ship surveillance and point-defense purposes. Profiles of vertical humidity (and thereby refractivity) are not readily measurable since the most rapid profile changes occur within the first few centimetres above the water surface. Apart from the fact that it would be very difficult to make measurements that close to the surface, the height of the surface is only constant when averaged over several minutes. In surface layer meteorology, semi-empirical relationships between fluxes of meteorological quantities and their profiles have been developed and so-called bulk measurements (i.e., point measurements at a reference height) are used to infer the meteorological profiles. The need for developing, improving, and validating evaporation ducting assessment has prompted several NATO cooperative efforts.

One effort was a joint U.S. - Greek measurement program in the strategically important eastern Mediterranean. With support from the University of Athens, the U.S. Navy established a propagation link between the Islands of Mykonos and Naxos in the Aegean Sea [*Richter and Hitney*, 1988]. The shore station at Mykonos used vertically spaced antennas for receiving signals in the 1 - 40 GHz range radiated from the island of Naxos, 35 km away. The link was

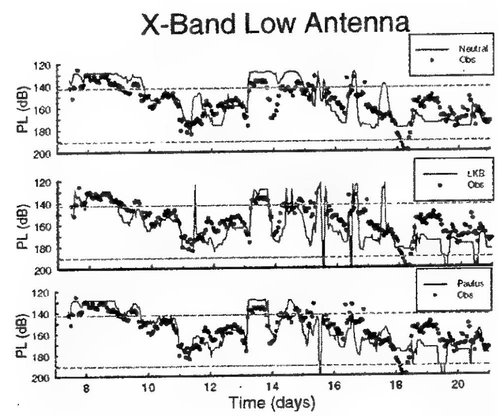

Figure 1. Evaporation ducting measurements and models.

operated during four measurement periods in different seasons, each lasting approximately two weeks. The objectives of these measurements were to gather statistical evaporation ducting data in this important geographic area, validate ducting models, and provide information on choosing optimal shipboard antenna heights for maximum detection ranges. An example of a two week measurement period is shown in Figure 1 where the dots represent measured path loss values at 9.6 GHz for a receiving antenna at 4.9 m and the transmitter antenna at 4.8 m above mean sea level. Most striking is the persistent signal enhancement of up to 60 dB over what would be expected under standard atmospheric conditions (the upper dashed line indicates free space path loss values and the lower diffraction path loss values).

In addition to the propagation measurements in Greece, another important cooperative initiative was the establishment of NATO DRG Panel 3 Research Study Group 6 (RSG 6). This group was chartered to "*investigate the low level maritime duct and its influence on microwave propagation*". RSG 6 was chaired by Professor Jeske of the University of Hamburg, Germany. At the time, he and his institution had performed the most comprehensive analyses and measurements with respect to evaporation ducting

[*Jeske*, 1965; 1971]. Participating nations in RSG 6 were Canada, Denmark, Germany, Italy, Netherlands, Norway, the UK, and the U.S.A. The group conducted meetings, measurement campaigns, and analyses and concluded its work in 1977. The final report states that "*for the evaporation duct well understood models are at hand*" [*Jeske*, 1977]. The conclusion, that evaporation ducting effects can be reliably assessed under operational conditions, has been proven by two decades of experience, even though the understanding of the physical processes governing flux-profile relationships in the surface layer have been and probably will be further improved [*Liu et al.*, 1979; *Fairall et al.,* 1996]. The prediction accuracy for evaporation ducting effects is not limited by an incomplete understanding of surface layer physics but by horizontal variability. Evaporation ducting is operationally significant primarily for propagation paths over tens to hundreds of kilometers. Over such distances, surface water temperature and surface layer properties will change thereby causing horizontally varying duct heights. This is the reason that newer evaporation duct models have not shown improved assessment accuracies.

Rogers and Paulus [1996] compared several models with different measurements. In Figure 1, they compare propagation model predicted signal levels using three different evaporation duct models (shown by the solid lines) with the previously described measurements in the Aegean Sea. The meteorological data used as input to the different models are based on shore measurements taken at the receiving site. In the top panel, *Jeske's* [1971] formulation is used with the assumption of neutral stability in the surface layer. The solid line in the centre panel shows calculated path loss based on the formulation of *Liu et al.* [1979] and the bottom panel a modification of *Jeske's* [1971] model by *Paulus* [1985]. All three models do a credible job in predicting evaporation duct enhancements with none of them showing a clear superiority over the other. The conclusion reached by RSG 6 almost two decades ago still holds today and data obtained in the cooperative efforts under NATO auspices remain an invaluable source of information.

The finding that evaporation ducting effects could be reliably assessed under operational conditions was one of the foundations that made the development of the first military microwave propagation assessment system possible. The Integrated Refractive Effects Prediction System (IREPS) [*Hitney and Richter*, 1976] was first operationally implemented in the late 1970s aboard U.S. aircraft carriers and is now part of the U.S. Navy's Tactical Environmental Support System (TESS) [*Sheridan et al.*, 1996]. IREPS was designed for shipboard over-water propagation assuming that the vertical refractivity structure remained constant throughout the region of interest. The assumption of horizontally invariant refractivity is a good first order approximation for open ocean environments and, using this assumption, the operational use of IREPS produced reliable results most of the time. There may be, however, spatial and temporal variations in refractivity fields, e.g., in the vicinity of weather fronts and in coastal regions. For propagation in range-dependent environments, a number of models were developed [*Dockery*, 1988; *Craig*, 1989; *Marcus*, 1992; *Barrios*, 1992]. A computationally efficient model for over-water propagation assessment in range-dependent refractivity environments is the Radio Physical Optics (RPO) model developed by *Hitney* [1992]. RPO is a hybrid model that combines ray optics and parabolic equation (PE) models.

Even though these models use certain assumptions and simplifications, their prediction accuracy is generally not limited by those assumptions but rather by the variability of the input data describing the refractive environment. The atmosphere changes, over the ranges and time periods of interest, sufficiently to make direct simultaneous sensing of refractivity along a propagation path impractical. There is, however, hope eventually to use inverse techniques to infer refractivity conditions from reception of appropriate radio signals themselves and combine this information with other data and high-resolution meteorological mesoscale models [*Rogers et al.,* 1996]. A recently developed assessment system is used to illustrate radio propagation assessment over terrain [*Hitney et al.,* 1996]. The assessment system, called Radio Propagation Over Terrain (RPOT), runs on personal computers in a Windows 95 environment and uses a combination of RPO and a terrain PE model (TPEM) developed by *Barrios* [1994]. Figure 2 shows an example of an RPOT coverage diagram for a typical shipboard radar against a small jet aircraft in the presence of a surface-based duct. The ship's location in the Adriatic Sea and the radar's pointing angle are depicted in the circle on the right-hand side of Figure 2. Radar coverage is displayed as probability of detection (*Pd*) which is more meaningful to an operator than path loss or signal levels. Figure 3 shows an RPOT coverage diagram, again in terms of *Pd,* for a radar typically found in airborne early warning aircraft against a small jet aircraft. The radar is located at an altitude of 18000 ft and the circle on the right shows, again, platform location and look angle. An elevated duct at 15000 ft causes a "radar hole" in the vicinity of this altitude for ranges larger than approximately 60 nmi. Similar displays can be generated for communications or electronic warfare applications. Displays for successive azimuth angles can be used to generate animated presentations. Terrain profiles are obtained from the National Imaging and Mapping Agency's Digital Terrain Elevation Data supplied on CD-ROMs. Environmental information is obtained either from the standard World Meteorological

Organization codes or entered manually from local sources.

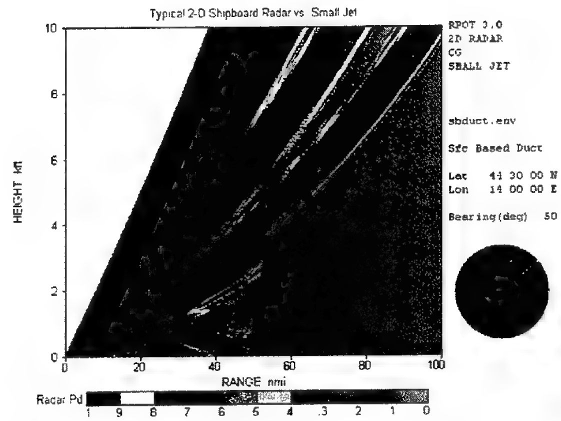

Figure 2. Coverage diagram for a shipboard radar against a small jet aircraft.

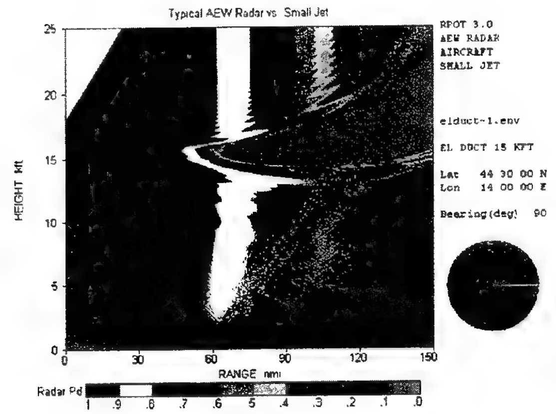

Figure 3. Coverage diagram for an airborne radar against a small jet aircraft.

These examples illustrate what is presently feasible and operationally available for real-time tropospheric propagation assessment. Further model development is needed to account for surface roughness effects and clutter under ducting conditions. Currently, propagation assessment limitations are timeliness and accuracy of environmental input data. Challenging and promising areas of research are refractive index profile inversion from passively received radio signals and development of high-resolution meteorological mesoscale models. Data assimilation systems that combine directly and remotely sensed data with accurate meteorological models are expected to provide accurate assessment of present and reliable forecasts for future propagation conditions. The development of such systems is an interdisciplinary R&D effort that requires broad cooperation and coordination. NATO's Research and Technology Organization is ideally suited to play a major role in this effort.

5. IONOSPHERIC RADIO PROPAGATION ASSESSMENT

Ionospheric Morphology

The ionosphere is an ionized region of the atmosphere in the altitude range 85 km to 1000 km, Figure 4. The ionisation is caused by several mechanisms. The most important of these, at non-auroral latitudes, are the sun's extreme ultra-violet (EUV), X-ray and Lyman alpha radiation together with solar cosmic rays. At high latitudes, particularly during magnetically active periods, the effects of energetic particles and electric fields are important.

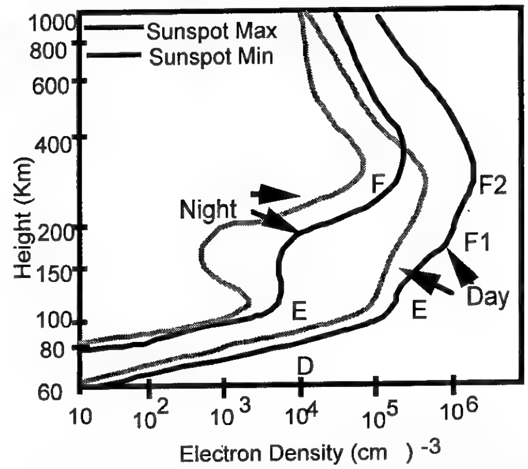

Figure 4. Typical electron density height profiles found in the ionosphere.

The rates of ionisation at any altitude depend on the atmospheric composition as well as the characteristics of the incident radiation at that height. As the solar radiation propagates down through the neutral atmosphere the various frequencies (energy bands) of the radiation are attenuated by different amounts. At the same time the composition of the atmosphere alters with altitude. Consequently, different ionisation processes predominate at different heights resulting in a layered structure. The principal layers are designated *D*, *E* and *F* (Figure 4), each being characterized by a different set of ionisation processes. Some of these regions are themselves layered or structured into the *E*, *Es*, *F1* and *F2* regions. The number of layers, their heights and their ionisation density vary with time and in space. The high latitude ionosphere is particularly complicated and will not be dealt with here but is described by *Cannon* [1989] and in general texts such as *Davies* [1981; 1990], *McNamara* [1991] and *Goodman* [1992].

HF Communications and Radar Decision Aids - HF EEMS

High frequency (HF) signals transmitted beyond line of sight (BLOS) propagate through the time and spatially varying ionosphere. To obtain high 'quality' and high 'reliability' operation, various system parameters such

as radiated power, operating frequency, antenna, modulation and data rate, should all be matched to the prevailing ionospheric conditions.

Based on the maximum usable frequency (MUF) some manual matching is often performed using daily frequency schedules. The chosen frequency can be estimated using HF prediction programs such as REC533A [*CCIR*, 1994a] and IONCAP [*Teters et al.*, 1983]. The operating frequency may also be measured in near real-time using oblique chirp ionosondes [e.g. *Arthur et al.*, 1994]. More often than not, however, the estimated operational frequency is simply based on a operator experience. This manual selection process is clearly limited. Furthermore, it is time intensive, often requiring an experienced HF operator and, frequently it results in sub-optimal configurations.

To overcome these drawbacks automated HF systems have been developed, for example ALE [*DOD*, 1988], and other advanced strategies such as ARCS, [*Arthur and Maundrell*, 1994]. These systems automatically and transparently match a number of system parameters (e.g. frequency and data rate) to prevailing ionospheric conditions.

Both the manual and the automated matching techniques are primarily concerned with maximizing link 'reliability' and 'quality'. Little attention is given to ensuring that the systems exhibit low probability of interception and jamming (LPI and LPJ). Generally, HF-LPI/LPJ procedures are based on techniques such as spread spectrum, cryptography, and antenna nulling. Even so the signals may still propagate to unwanted or unauthorized receivers causing interference or resulting in the transmission of intelligence. An alternative technique, based on the tactical use of signal propagation [*Argo and Rothmuller*, 1979; *Goodman et al.*, 1982], may often be more advantageous. The tactical technique exploits detailed knowledge of the ionosphere and ray-tracing to minimize the signal coverage and thereby deny, or minimize, the hostile receivers access to the radiated electromagnetic energy. The technique can be used in isolation or in conjunction with more sophisticated LPI/LPJ techniques.

Although this tactical technique could be performed using current prediction programs it is operator intensive. Specialist data (e.g. location of interceptors and frequency plans) are required and the process cannot be performed by inexperienced HF operators. Additionally, skywave prediction programs fail to address the contribution of the ground wave component which may be significant at low frequencies and at short ranges.

To overcome these deficiencies a tactical HF decision aids known as HF EEMS (HF Electromagnetic Environmental Modelling System) is being developed. The aid is designed to enable both HF experts and inexperienced operators to predict, those communications system parameters such as frequency, receiver station , and radiated power, which optimize the HF system. Some aspects of the decision aid and its LPI/LPJ utility have previously been described by *Shukla and Cannon* [1995] and *Shukla et al.* [1996] In this first version of the decision aid a modified version of the REC533 prediction program performs the functions of the ionospheric propagation and communications prediction models.

HF-EEMS V1.1 contains a simple ground-wave propagation model for line of sight (LOS < 200 km) systems. The ground-wave propagation characteristics are calculated by a modified version of GRWAVE [*CCIR*, 1994b], which computes ground wave field strengths over a smooth, curved, homogeneous earth.

To minimise 'operator' input the 'expert' first populates the decision aid with a list of transmitter and receiver station characteristics (e.g. latitude, longitude, receiver bandwidths, noise power). The expert must also input operational frequencies and update the sunspot number data file. After the decision aid has been populated the 'operator' selects the transmitter, receivers and hostiles from the previously entered data base.

The decision aid displays data to the *operator* in two formats: signal coverage maps, and frequency tables. In Figure 5 both the skywave and ground-wave signals (the latter as concentric circles) are shown on the same map, along with friendly and hostile stations locations. These monthly median maps enable users to inspect communications link configurations and evaluate the effectiveness of broadcast transmissions. Figure 5 is the May 1997, 12 UT, SNR signal coverage map at 24 MHz and shows the broadcast signal being received by two friendly stations and denied to one hostile station.

To aid data interpretation, signal coverage statistics for the full viewing area and for each hostile intercept

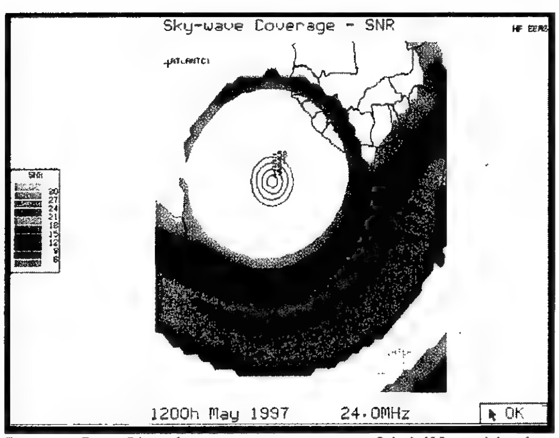

Figure 5 Signal coverage map at 24 MHz with three friendly stations (+) and two hostile stations (x).

region (HIR), a 5 degree box centred on the hostile, can be displayed in 3 dB SNR increments. The coverage statistics for each HIR are used to allow for inaccuracies in the ionospheric and ray-tracing models.

Via a table, the decision aid recommends the best operating frequencies to minimise hostile interception. There are two approaches which can be employed, one based on LUF (lowest usable frequency) considerations and the other based upon the MUF. In the former the aim is to operate on a frequency which is below the LUF to the hostiles but above the LUF to the friendly receivers. The latter approach aims to choose a frequency which is above the MUF to the hostiles but below the MUF to the friendly receivers. It is to be noted that the LUF technique is more problematical since it relies on signal strength estimates which are more difficult to achieve than MUF predictions.

Figure 6 is an extract from a 24 hour colour coded frequency table, based on MUF predictions, for the broadcast scenario shown in Figure 5. If mode support is predicted the table gives a frequency range within which all friendly stations will receive the signal, whilst minimising hostile interception. The frequencies in the allocated frequency plan which fall within this frequency range are also shown. The column on the far right of Figure 6 shows those hostiles predicted to intercept the broadcast transmissions. The hostile displayed is that most likely to intercept the signal; additional hostiles are listed in decreasing order of interception probability in the drop down box. Frequencies ranges not intercepted by hostiles are coloured green (e.g. 15-19 UT). Those intercepted by at least one hostile (e.g. 20-21 UT) are coloured yellow to indicate that caution should be employed. If all hostiles intercept the signal (e.g. 12-14) then the frequency range is coloured red. As such, transmissions should be avoided unless vital.

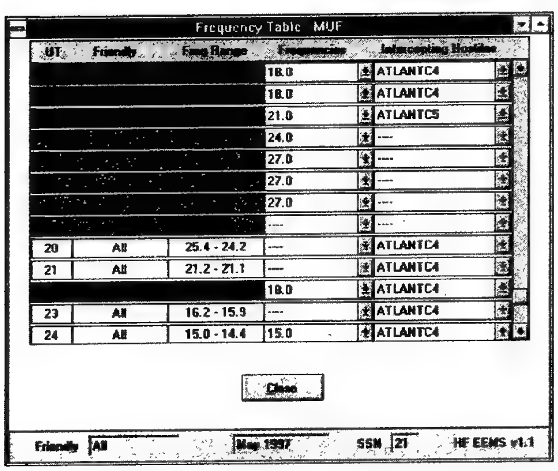

Figure 6 Frequency ranges which minimise hostile signal interception during signal broadcasts using the MUF algorithm

In the future a more accurate propagation model using the analytic ray-tracing technique (SMART) developed by *Norman and Cannon,* [1997] will be incorporated into HF-EEMS. Although improvements to the median ionospheric model will initially be achieved using the pseudo sunspot number updating techniques [*Uffleman et al.*, 1982; *Shukla and Cannon,* 1994], it is planned that an improved ionospheric specification model such as PRISM (see below) will ultimately be used.

PRISM Ionosphere Specification Model

As noted in Table 1, the performance of a wide variety of military communication, surveillance, tracking, and navigation systems are controlled by the ionosphere. Often, because the ionosphere is a complex and dynamic environment, empirical or climatological models (such as those used in the aforementioned REC533 and IONCAP) are inadequate for the specifications and forecasts required by modern operational RF military systems. However, the exploitation and integration of a number of rapidly evolving technologies, including ground- and space-based sensors, data fusion, high speed computing, and the internet, promise a greatly enhanced specification capability.

An example of this emerging capability is the on-going development of the Parameterized Real-Time Ionospheric Specification Model (PRISM), now operational at the U.S. Air Force Space Forecast Centre [*Daniell et al.*, 1995]. It is a physical (first principles) model that can be driven in real-time by ground- and space-based sensor data, to provide electron density and ion profiles globally, every two-degrees in latitude and every five-degrees in longitude, from 90-1600 km altitude. PRISM provides specifications of the auroral boundary, the high latitude ionospheric trough, and the enhanced densities associated with the Appleton equatorial anomaly. These outputs can be adjusted on the basis of near real-time sensor data, including: bottomside electron-density profiles from digital ionospheric sounders; total-electron-content (TEC) data from GPS ground-receiving sites; energetic particle fluxes and auroral boundary data from SSJ/4 satellite sensors; 840 km altitude in-situ electron/ion densities, and temperatures and velocities from the SSIES satellite.

In the future these data will be further enhanced by ultra-violet (UV) data from the Defense Meteorological Satellite Program (DMSP). The capacity and requirement for monitoring and sensing of the battlespace environment is rapidly increasing. Consequently we envisage further enhancements such as measurements of other important solar/geophysical parameters, such as the solar EUV flux, thermospheric winds, equatorial and polar drift velocities, and parameters to specify accurately geomagnetic activity [*Daniell*, 1995]. As the variety and quantity of such

sensor data become available, it is anticipated that the errors in the specification of the ionosphere on a global basis will be reduced from (roughly) 35% to below 5% over the next decade, thereby leading to significant reductions in errors and outages associated with a number of military systems.

An important use of ionosphere specification models is to couple them with radio wave propagation prediction codes to provide tailored products for specific military system applications, including ionospheric corrections required by trans-ionospheric surveillance and tracking radars and the GPS navigation system, and for frequency management of HF communication and radar systems. An example of the latter is illustrated in Figure 7, in which ray trace calculations are shown for a HF over-the-horizon radar located in the northeast United States and transmitting to the south. A PRISM specification of the ionosphere along the propagation path is also shown (colour coded in terms of plasma frequencies) above the ray traces, including distinct ionization crests associated with the equatorial anomaly on both sides of the geomagnetic equator.

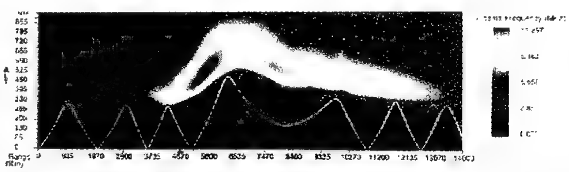

Figure 7. HF numerical ray trace computations using PRISM ionospheric specifications along the propagation path.

The orange ray (Figure 7) corresponds to a radar signal with a frequency and elevation angle which is too high for the ionosphere to refract back to earth. The red ray corresponds to a signal at a lower frequency and launched at a lower elevation angle; this propagates to great distances via a number of hops between the ionosphere and the ground. The ray trace in white corresponds to a signal of the same frequency as that in red, but launched at a steeper elevation angle. It too propagates to great distances via successive hops between the ionosphere and the earth, except in the vicinity of the geomagnetic equator approximately 6500 km down range. There it is ducted (effectively) at very high altitudes, owing to the intensity and location of the ionisation crests associated with the equatorial anomaly and the propagation geometry for that specific signal frequency and elevation angle. For this case, the display shows that there would be a hole in the HF radar coverage in the equatorial region, thereby necessitating a change in the operating parameters of the radar to insure coverage in that region.

SMART - Analytic ray tracing technique

Numerical ray tracing is often too slow, yet the use of the computationally fast mirror refection approaches based around Martyn's theorem [e.g. *Davies*, 1990], which are used in prediction models such as REC533, are not accurate enough. Recently a new class of ray tracing, known as analytic [e.g. *Dyson and Bennett*, 1988], have been developed for ground to ground and trans-ionospheric applications. SMART (Segmented Analytic Ray Tracing) [*Norman and Cannon*, 1997] is able to accommodate ionospheric tilts to an accuracy of 2-3% whilst providing an order of magnitude improvement in computational efficiency relative to the numerical ray tracing.

Specification/Forecasts of Ionospheric Scintillation

The effects of naturally occurring disturbances in the ionosphere can be especially severe on the performance of a variety of important military RF systems, causing serious disruptions and even blackout for extended periods, over very large geographical areas. Many of these are associated with turbulence in the ionosphere, typically above 150 km altitude, which produce irregularities and steep gradients in electron density which scatter trans-ionospheric radio waves in the VHF and UHF bands, thereby generating rapid amplitude and phase fluctuations (scintillation) in the signals. The effects of scintillation on military RF systems are varied [e.g., see *Basu et al.*, 1988; *Klobuchar*, 1991; and *Aarons and Basu*, 1994], and include: message errors in trans-ionospheric satellite communication links produced when signal fades exceed the fade margins of the receiving systems. They also include data loss and cycle slips in GPS navigation systems caused by amplitude scintillations; and loss of lock or tracking in narrow band GPS receiving systems produced by rapid frequency changes in the received signal that are greater than the receiver bandwidth. The latter can be produced by severe phase scintillations, even without simultaneous deep amplitude fading.

The severity of ionospheric scintillation varies with frequency, location, season, and sunspot cycle [*Basu et al.,*1995]. Scintillation effects decrease with an increase in signal frequency over the VHF/UHF bands, but frequencies as high as 10 GHz can be affected. The source of the most severe scintillation effects is the post sunset equatorial anomaly region (roughly +/- 15-degrees north and south of the geomagnetic equator). In this region the seasonal variations in scintillation exhibit a marked dependence on longitude. For example, in the American sector, the occurrence of scintillation is maximum during the months of September to April, and minimum during the May to July period; whereas, in the Pacific sector occurrence of scintillation is minimum during November to January, but is relatively constant and maximum throughout the rest of the year. Other active regions of severe ionospheric scintillation are located at the auroral and polar cap latitudes. At mid-latitudes, however, scintillation effects are usually not significant. Severe scintillation disturbances occur throughout the 11-year solar cycle (especially in the equatorial region), but

they can be especially severe near solar maximum. During the most recent solar maximum period (1988-1992), fade depths exceeding 10 dB at GPS frequencies were measured at Thule, Greenland. During the same period, 20 dB fades at GPS frequencies were often observed in the equatorial anomaly region. At lower frequencies, UHF satellite communication outages are expected to increase five-fold during solar maximum, compared to those experienced during solar minimum.

Long term research has shown that, at high latitudes, scintillation conditions are closely linked to magnetic and solar activity levels, and, are therefore highly variable and presently difficult to forecast in a timely and reliable manner. Equatorial region scintillations, by comparison, follow a regular diurnal and seasonal variation as mentioned above. Studies have revealed that at least two types of F region irregularities arise in the equatorial region after sunset which give rise to scintillation; namely, those related to plasma bubbles (e.g., see *Ossakow,* 1981; *Kelley,* 1989) and others called bottomside sinusoidal irregularities (*Valladares et al.,* 1983). The bubbles originate after sunset in the bottomside F region and become highly structured as they penetrate to altitudes exceeding one thousand kilometres above the geomagnetic equator. The extended bubbles then map out along the geomagnetic field to the equatorial anomaly regions of +/- 15 degrees magnetic latitude causing scintillation effects as they drift eastward and slowly decay prior to sunrise. In contrast, the bottomside irregularities are limited in altitude extent and are confined over a relatively narrow latitude range around the geomagnetic equator.

Such knowledge has led to the recent development by the U.S. Air Force's Phillips Laboratory of a ground-based sensor technique (SCINDA) to provide timely and reliable specification and warning of equatorial ionosphere conditions that will disrupt C3I systems. As illustrated in Figure 8, satellite receiving stations have been established in Peru near the geomagnetic equator and in Chile, at a site 11-degrees south magnetic latitude. Each station uses spaced antenna scintillation receivers to monitor 250 MHz transmissions from two geostationary satellites, one in the west and the other to the east. The green and red lines depict the signal propagation paths from the geostationary satellites to the two receiving sites, with red indicating that the signal is experiencing scintillation (disturbed propagation) conditions and the green indicating undisturbed conditions.

Data from the sites are transmitted to a central location via the internet and are used to drive computer-based physical and climatological scintillation models, which generate near real-time, three-dimensional graphic displays depicting the onset, location, movement, and relative severity of the ionospheric scintillation. An example of such a display is also illustrated in Figure 8, in which the wedge-shaped structures depict three-dimensional regions in the ionosphere that are producing scintillation, based on the observed data and model outputs. The regions are colour coded to indicate the relative severity of the scintillation associated with them. As shown, the green, yellow, and red features correspond to 99-percentile fade levels of < 6 dB, 6-12 dB, and > 12 dB, respectively, for the signals passing through those regions in the ionosphere.

MODERATE

Figure 8. Display of equatorial ionospheric scintillation regions that disrupt C3I systems.

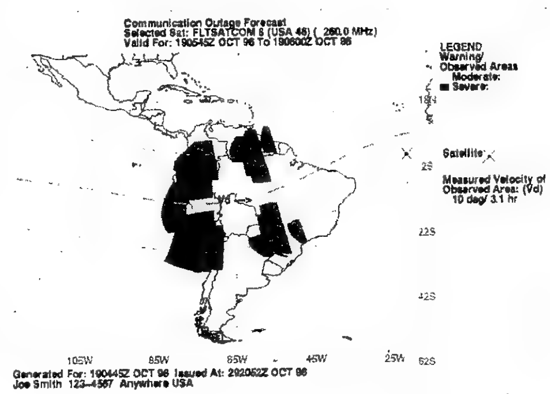

Figure 9. Two hour forecast (footprint) map for communication to a geostationary satellite at 20^{O} E.

Other SCINDA displays generated from the observation and knowledge of such structures include colour-coded "foot-print" maps indicating how severely individual UHF/L-Band communication and GPS-navigation satellite-to-ground links are being affected, anywhere on the ground within the theatre of operations; and 2-3 hours advance warnings of the scintillation conditions that should be expected later within that area. Such a warning map is given in Figure 9, which shows a two hour scintillation warning forecast, derived from the observations shown in Figure 8, for communication links in the South American sector to a geostationary satellite located at a longitude

of 20-degrees east. Similar outage warning maps can be derived and displayed by SCINDA for any other satellites that may be in view. In addition, individual displays generated throughout the periods of ionospheric scintillation events can be used to develop animated presentations, having application to modeling and simulation studies of the effects of scintillation on other operational or planned C3I systems.

6. THE WAY AHEAD

Electromagnetic propagation assessment is crucial in the development of a wide range of sensor and weapon systems. It is required for military planning, for real-time operations and, in connection with operational decision aids. It has an important role in the new NATO strategy. Propagation assessment supports improved flexibility, mobility, improved situational awareness and improved training techniques. Above all, propagation assessment and related decision aids allow more effective and efficient use of available resources.

Decision aids and environmental models already form part of a number of contemporary systems but many challenging tasks remain in all regions of the RF electromagnetic spectrum. Of major importance is the timely and accurate specification of the propagation environment. This will require the development and deployment of a wide range of sensors.

7. ACKNOWLEDGEMENTS

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From Information Warfare to Information Power
A New Paradigm for National Security in the Information Age

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The passage of the Goldwater-Nichols Act in 1986 generated a new emphasis on "jointness" in the American military. Current concepts of jointness and joint operations are encapsulated in the existing definition found in Joint Publication 1-02, which defines joint as "activities, operations, organizations, etc., in which elements of more than one *Service* [emphasis added] of the same nation participate." The question at hand, however, is whether this concept, centered on blending the operations and capabilities of the four military Services, is sufficient for information warfare (IW) and the needs of national security in the information age. Are the impacts and implications of the information revolution so widespread that they necessitate a new perspective on who should be covered by the umbrella of jointness? The thesis of this paper is that the current Service-focused understanding of jointness is insufficient because it is too narrow, and that a broader and more inclusive concept that incorporates all of the various elements of national information power is necessary.

The Services and IW

All of the American military Services are responding in some manner to the challenges of the information age and the imperatives of information warfare. The Marines, while uncertain about the broader theories of IW, are deeply involved in exploring the means by which Marine forces can attain "command dominance" over its adversary. While acknowledging and leveraging the recent dramatic technological advances in information and communication systems, the Marines' focus is clearly on the human dimension of conflict, with the objective of maximizing human and operational flexibility instead of relying on technology to minimize friction. The Army, also cautious about the broader theories of IW, has no such qualms about the technological opportunities of the future, and the Army's vision for the next century, incorporated in "Force XXI" and the "Army After Next", based on digitization of the battlefield, is heavily, perhaps critically, dependent on the technologies of the information age. The Army is investigating the means and implications of these concepts and capabilities, and its Land Information Warfare Activity (LIWA) is one of the Army's focal points for this effort. Another is its Training and Doctrine Command (TRADOC), which recently issued the Army's first doctrine manual in this area, Field Manual (FM) 100-6, "Information Operations." (The exact meaning of "information operations" varies according to the user, and while the term is used by the DOD, Army, and Air Force, it means something different to all three.)

The Navy has possibly more personnel engaged in "nuts and bolts" information operations than any other Service and has (perhaps more than any other Service) for decades practiced some of the elements of Command and Control Warfare (C2W), defined as "the military strategy that implements information warfare on the battlefield." While still exploring the broader ramifications of IO, the Navy is exercising and practicing it increasingly in its daily operations. While the Naval Information Warfare

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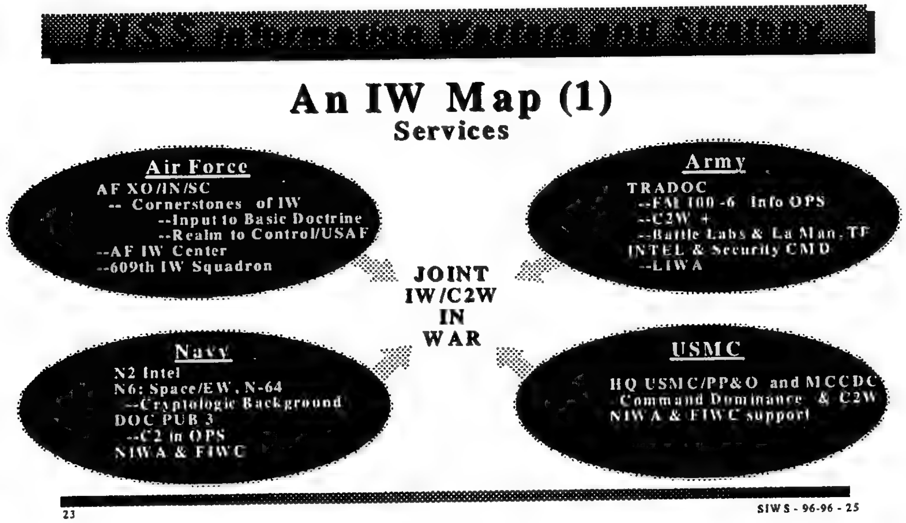
Activity (NIWA) at Fort Meade is a geographical reflection of the Navy's long history of cryptology, the Fleet Information Warfare Center (FIWC) and its several branches around the country

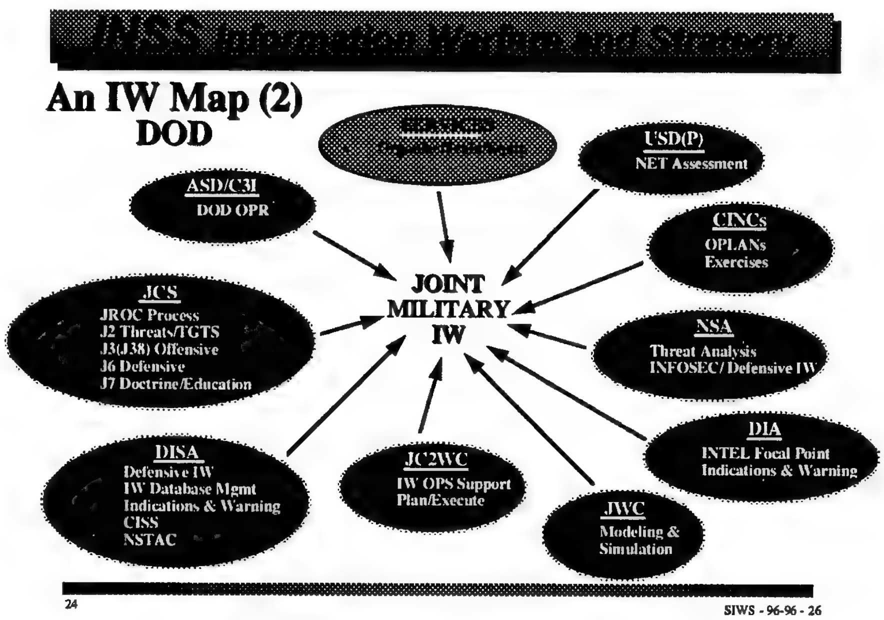


are heavily involved in developing and refining concepts for fleet IW/C2W operations. The Air Force has taken dramatic steps, both organizationally and doctrinally, to move into information age warfare. In 1993 the Air Force established its Information Warfare Center around what had been its Electronic Warfare Center, and the newly-activated 609th IW Squadron is the first unit dedicated to an operational IW mission. The Air Force's white paper "Cornerstones of IW", published over the signatures of Dr. Sheila Widnall, Secretary of the Air Force, and General Ron Fogleman, Chief of Staff, expresses the broadest view of IW of any of the Services, stating information is a "realm" to be dominated in a manner alike to other operational environments such as the air or space. Evolving doctrinal concepts speak to the need to integrate Air Force operations across three realms--air, space and information--in order to attain superiority and freedom of action in each. Joint IW, therefore, involves integrating and coordinating IW across the doctrinal, organizational, and conceptual differences of the four Services.....right?

IW in the DOD

Here is where the paradigm of jointness begins to change, because any discussion of IW that does not take into account the capabilities, responsibilities, and operations of a range of DOD organizations and agencies apart and aside from the four Services is incomplete. The most immediately apparent are those that respond directly to the Chairman of the Joint Chiefs of Staff or through the Joint Staff, or are in the direct chain of operational command through "the CINCs"--the Unified or Theater Commands. The CINCs are the most obvious players, because they are charged with the responsibility of planning for and conducting IW, and the Chairman JCS has issued detailed guidance with the publication in early 1996 of CJCS Instruction 3210.1, "Joint IW Policy." The Unified Commands are each exploring means to integrate information warfare into their plans and operations; indeed, some see it as a centerpiece of their

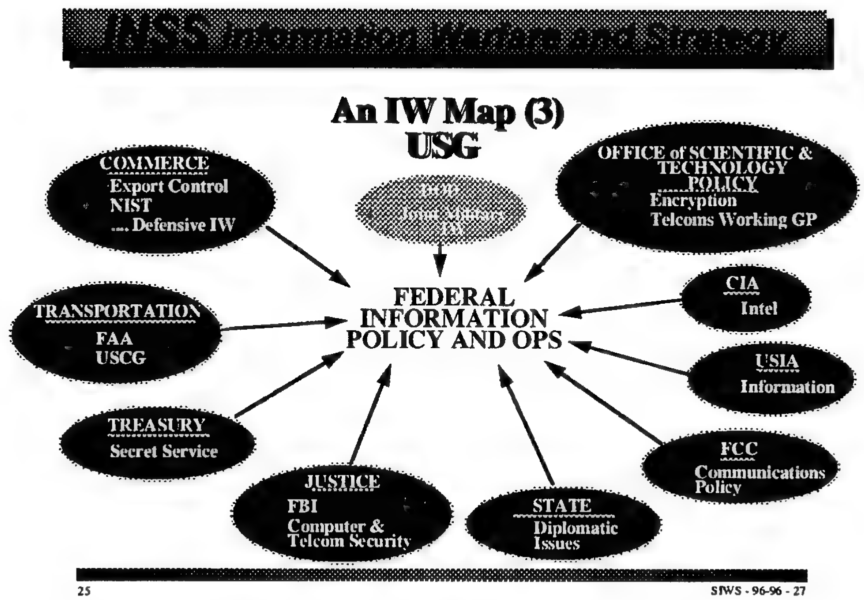
future mission. The Unified Commands are jointness personified, as is the organization charged with supporting their IW/C2W efforts, the Joint C2W Center, collocated with the Air Force Information Warfare Center. Information warfare in the real world simply is not possible without these elements of the joint force. Other members of the joint community also contribute to our IW capability. The Joint Warfighting Analysis Center, Joint Doctrine Center, and Joint Warfighting Center, for example, all have a role in shaping our IW capability, as do the elements of the Joint Staff such as J-6 or J-3, which serves as the OPR for joint IW/IO matters.



Several DOD organizations outside of the JCS, however, are equally critical to our national IW capability. The Defense Information Services Agency (DISA) manages DOD communications systems and is one of the most critical players in the effort to provide information assurance and security to DOD communication systems. DISA, through the National Communications System (NCS), provides the DOD's interface with the National Strategic Telecommunications Advisory Council (NSTAC), which is comprised of the chief executives of the nation's largest telecommunications firms and which meets to provide the President with strategic advice on matters relating to telematics (the marriage of telecommunications and computer networks) and information policy. The Defense Intelligence Agency is the internal DOD focal point for intelligence matters relating to IW, while the National Security Agency is a key player in the effort to analyze the threat and provide information security and defensive IW. Any discussion of national information power and security must take into account the responsibilities and capabilities of these agencies, and no discussion of "joint IW" would be complete without them. A comprehensive approach to joint IW, therefore, requires coordinating the activities and policies of several Joint and DOD elements as well as the Services...right?

IW in the Federal Government

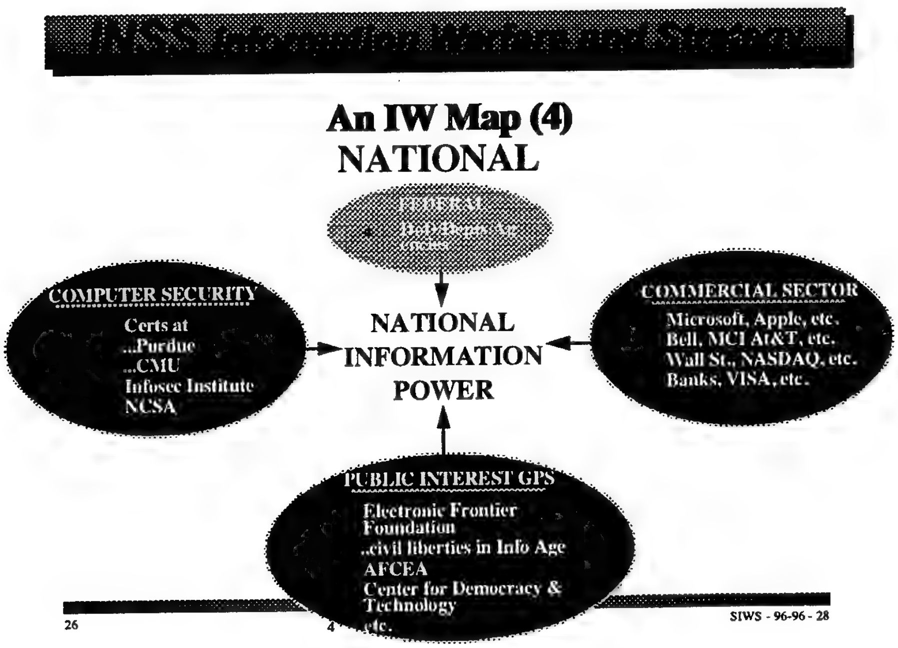
This is where the paradigm of information warfare begins to get really unsettling for the traditionalist, because from a national security perspective several other elements of the federal government are crucially important to the use of information for national security, the development of national information power, and the conduct of IW in its broadest conceptual sense. The Central Intelligence Agency is the focal point for national security intelligence. This not only includes potential threats to national capabilities, systems and infrastructures but also the rapidly expanding world of "open source intelligence", and the CIA is wisely and aggressively looking at ways to incorporate this new and technologically-driven source of information into its processes and databases. Other key providers of American information power are the United States Information Agency (USIA) and the Voice of America (VOA), and although their staffers would bristle if told they were involved in IW, the use of information as a weapon in the "contest of ideas" and the worldwide nurturing of democracy clearly fits into a larger and more inclusive view of IW. One might wonder what role the Justice Department has in IW, but Justice is one of the core members of the President's Commission on Critical Infrastructure Protection, established in mid-1996 with President Clinton's Executive Order 13010, and the Federal Bureau of Investigation is conducting an ever-increasing number of investigations into computer crime and cybernetic espionage. The Bureau has an active program underway in computer and telecommunications security. If a DOD or other federal computer system suffers a break-in or intrusion, the FBI will almost certainly be one of the first agencies called. The Commerce Department's Office of Export Control and National Institute for Standards and Technology (NIST), the President's Office of Scientific and Technology, and Office of Management and Budget are involved with issues such as electronic data encryption and national information infrastructure policy. These might not seem like national security issues to a traditionalist warrior, but similar issues are becoming increasingly important to areas such as technology exports, terrorism, or the war on drugs, all of which have some degree of current military interest or involvement. Most other federal agencies increasingly rely on the smooth and uninterrupted flow of electronic digital information to carry out their functions and thus have interest and involvement in national information power. Thus, the paradigm of joint IW/IO must incorporate not only the Services but the Joint, DOD, and Federal communities as well.....right?



National Information Power

It is at this level that the paradigm of joint information power reaches a perspective at once very broad and most troubling for traditional concepts of "jointness" focused on military services. The "defense" of cyberspace (that place where computers and electronic telecommunications systems connect and interact, a field of study known as "telematics") is being waged in part by entities such as the computer emergency response teams (CERTs) at universities such as Purdue or Carnegie Mellon. Information age "warriors" are trained not by military drill instructors but by computer science departments all around the country. Educational organizations such as the National Computer Security Association or the Infosec Institute play a role here. A wide range of public interest groups represent all points of the political and social compass, from the National Military Intelligence Association and Armed Forces Communications & Electronics Association to the Center for Democracy and Technology and the Electronic Frontier Foundation. They all help shape and set the political terrain and social context for the ongoing evolution of information age security issues. Finally, and certainly not least, there is the commercial sector, because the issues involved in information age security would be meaningless without the activities, advances, and involvement of Microsoft, AT&T, NASDAQ, Citibank, etc. The information revolution is, at heart, not a military revolution but a commercial, cultural and technological one, albeit with extremely important impact on and implications for the uniformed military. The DOD is not leading

this revolution but running fast to merely stay abreast of the changes in technology and society.



From Information Warfare to Information Power

National security in the information age and the development and exercise of the information component of national power requires a new paradigm of jointness that incorporates and synchronizes the policies and activities of all the players in the information realm. The development and exercise of national information power spans the organizational spectrum from the members in a military IW unit to the leadership of the largest information related corporations and commercial entities. Although the DOD cannot direct these widespread activities, the paradigm of Joint IW must of necessity encompass military, governmental, and private sector organizations and actions. This will require changes both organizational and cultural that will allow discussion and coordination of activities, even if the coordination is informal and non-directive. Perhaps the recent formation of the President's Commisison on Critical Infrastructure Protection presents a baseline model for the integration of federal and private sector concepts and activities. Within the military Services, doctrines for IW/IO must take into account the dual nature of information power and help to set a mindset that sees the civil sector as a partner in the new paradigm of information age jointness. Without such a paradigm, information age national security increasingly will become a chimera towards which we will strive but find unattainable.

You will note that I have not yet mentioned in this paper "the definition" of Information Warfare. What, after all, is IW! The seemingly endless series of changes in the official DOD definition of information warfare--a different one in each of the three years the School of Information Warfare & Strategy has existed--reflects the lack of conceptual certainty about what IW is and where it fits into the

range of elements of national power. The intent of this paper is to suggest an approach that builds to an understanding not just of IW, but how it fits into the full range of national information power.

Command-and-Control Warfare: C2W

In March 1993 the Joint Chiefs of Staff published Memorandum of Policy (MOP) 30, which defined and established guidelines for Command-and-Control Warfare, or C2W, which is perhaps best understood as the "strategy that implements IW on the battlefield." This is IW's most basic building block, its foundation in a sense, and it incorporates a range of operations the military understands quite well: Psychological Operations (PSYOP), Operational Security (OPSEC), Deception, Electronic Warfare (EW), and physical destruction of vital C2 nodes. Since the first three of these have been recognizable elements of warfare since biblical times the immediate question is "what's new about C2W?" These activities have, for the most part, been conducted by small and isolated groups of little known and frequently less well regarded specialists, so that there was usually little coordinated effort to integrate them into a unified whole and build on the synergies between them. This narrow approach thus forfeited much of the advantage to be gained by integrating these operations, such as the relationship between psychological operations, deception, and operational security. The fundamental intent of MOP 30 (rescinded in early 1997) and now Joint Pub 3-13.1, "Joint Doctrine for C2W", is to break down the organizational barriers and integrate the various elements of C2W so that their synergies and relationships can be magnified.

One of the hallmarks of C2W is that it can be conducted in any or all of the different warfighting environments--land, sea, air, outer space, even cyberspace--by any or all of the warfighting Services. The objective of C2W is the incapacitation of the enemy's military C2 function, by operations against the enemy's C2 target set and the protection of one's own. The targets that comprise this set can be physical, such as a command center, communications switching system, or planning cell, or cognitive, such as the morale and fighting spirit of the enemy forces, or the enemy commander's knowledge of friendly forces. The means that can be employed towards these ends vary from the traditional, such as leaflets, radio broadcasts, or high explosive, to the use of radically new technologies, such as anti-satellite weaponry or even the internet.

Military Information Warfare

The greatest difficulty facing the development of IW today is not technological but conceptual, because there is no common understanding or acceptance of what constitutes IW. The latest definition, "Information Operations conducted during time of crisis or conflict to achieve specific objectives over a specific adversary or adversaries", (established by the latest version of DOD Directive 3600.1, signed on 9 December 1996 after more than a year of coordination, rewriting, recoordination, and wrangling over its content) is hardly enlightening even to the members of the IW community who know how "information operations" are defined. IW, however, should not be complicated: it consistsof *offensive and defensive warfighting actions in or via the information environment to control and exploit that realm*. The obvious

parallel to other forms of warfare, such as air or maritime warfare, helps to clarify what constitutes IW, and also helps to avoid two of the main problems facing IW, either defining it too broadly or too narrowly. Some concepts of IW are so broad they essentially make all other human activities subsets of IW, while others reduce IW to little more than an umbrella for a series of separate activities. Neither approach is accurate or conducive to a better understanding of IW. The suggested definition helps to clarify that IW is a military activity carried out in or via the information environment.

Which leaves open the question: what kinds of activities or operations constitute military information warfare? Since C2W is a subset or component of IW all of its elements comprise IW, in the same sense that close air support is a component element of air warfare or antisubmarine warfare is part of war at sea. So how is IW different from C2W? A major aspect of IW is the effort to seize and maintain control of the information environment, which leads to what the DOD calls information superiority or information dominance. This concept is not part of C2W. The Air Force, in its visionary white paper "Cornerstones of Information Warfare", incorporates "counterinformation operations" as part of the effort to gain and maintain control of the information environment, control meaning the ability to use the environment for our purposes and deny it to our adversary. The parallel to the Air Force's doctrinal belief in "counterair operations" as part of the effort to gain and maintain control of the air is both unmistakable and very useful. The destruction of a communications switching center, for example, whether by an airstrike, special operations team, or malicious computer code modification is information warfare because the objective is to gain control of the information environment. These examples, of course, might also be aerial warfare or special operations. One of the conceptual problems to be faced is the realization that the urge to place activities into categories can be counterproductive to a fuller understanding of the relationship between the ends sought and the means used to attain those ends. Information as an environment may be a difficult concept to grasp, but there is no arguing that there is a physical environment to which information is uniquely related: cyberspace. Cyberspace *is that place where computers, communications systems, and those devices that operate via radiated energy in the electromagnetic spectrum meet and interact*. A radar or radio jammer is an IW device; implanted computer code that affects an adversary's computer system via a "logic bomb" is an IW device; and a videotape altered via computer "morphing" to influence an adversary's political stability is an IW device. Note the synergies between IW and other forms of warfare, as cited previously: disabling an enemy air defense computer with either a bomb or a virus can be both air and information warfare, given the means employed and the effect sought.

Strategic Information Operations

The current DOD definition of Information Operations, "Actions taken to access and/or affect adversary information and information systems while defending one's own information and information systems" is only slightly more descriptive than the definition of IW. Is the military the only branch of government that uses information for strategic purposes, and solely during wartime? Of course not, which

necessitates a larger concept that incorporates the other governmental actors that engage in information operations for strategic purposes. This concept is "strategic information operations", defined as those *military and governmental operations that protect and exploit the information environment to attain strategic objectives.* This highlights the fact that competition and conflict in the global information environment is a constant affair not contained within the narrow confines of "wartime." The information struggle, which President Ronald Reagan called the "worldwide war of ideas", goes on during peacetime and crisis as well as war, and it involves a far broader range of actors than armed military forces. A prime example of a strategic information operation was that multi-year effort to influence the populace of not only the Iron Curtain countries but the USSR itself via Radio Free Europe and its associated programs. Another, which did occur during wartime, was the successful effort by the British in the opening days of the First World War to dredge up from the bottom of the North Sea the underwater telegraph cables that connected Germany to the outside world. This strategic information operation not only cut Germany's military C3 links to its forces worldwide (at sea and in its colonies) but also, and more importantly, meant that the neutral countries of the world, most especially the United States, saw the war through a filter located in London. These two examples highlight the use of information for strategic political objectives.

Strategic information operations thus differ from military information warfare in two important ways: IO spans the conflict spectrum from peace to war and back to peace, and it involves all elements of the national government, not solely the military. These are important considerations precisely because the effort and coordination needed to engage the entire range of governmental organizations is a particularly difficult and sensitive affair, and the word "war" has been a stumbling block to gaining understanding and acceptance of the concepts surrounding information warfare. An information-intensive non-military organization such as the Voice of America may be very uncomfortable with the concept of information *war*fare, yet see an important role for itself in strategic information *operations.*

National Information Power

Does the exercise of national power in the information environment rest solely with the national government, whether through its military or civil organs? No, because national information power is the *broadest range of military, governmental and civilian information capabilities that enable national-level exploitation and dominance of the information environment.* It is at this level that information steps up onto the platform with economic, military, diplomatic, technological, and other forms of national power to provide national leadership with the fullest range of power to use in attaining national strategic objectives. Note that none of these forms of power function in a vacuum, and all are synergistically related to the other forms: the art of statecraft rests in how one integrates them. Also note that perhaps the key operative word in this definition of information power is *capabilities,* for it is in the judicious weighing of the military, governmental and civilian components of information power that the potential emerges to blend and use them to achieve national strategic objectives.

A critical factor here is that the revolution in information technologies is being driven by the civil sector, not the government or military. The civilian component of national information power thus includes such diverse elements as our telematics infrastructure, our satellite communications systems, our microprocessor ("chip") production industry, and our software developers and producers. Other even less obvious elements, such as the computer science departments of our colleges and universities, or even the news media, also make important contributions to national information power,. All of these contribute to the national ability to exercise power and influence people, organizations and governments through the information environment. This conjoining of the military, governmental and civil capabilities and information potential is the source of national information power. This is the new paradigm of national security in the information age.

Paradigm K

National Information Power (eg. air/space power):
- Broadest range of military, governmental and civilian capabilities; exploit the environment & dominate strategic context
- Strategic level to attain national security objectives
- SATCOMs, national telmatics network (eg. Boeing, NASA)

Strategic Information Operations (eg. air/sea/space):
- Wide range of military and governmental operations to protect and/or exploit the environment
- Spans the conflict spectrum (peace--war--peace)
- Computer netwar, Radio Free Europe (eg. Berlin Airlift)

Military Information Warfare (eg. air/sea warfare):
- Offensive & defensive warfighting actions to control/exploit the environment
- Includes C2W
- Counterinfo (eg. air/sea control)

C2W (information tech in war) Mil Ops by/in Air, Sea, Land, Space, & Info
- 5 Elements plus... Leaflets, HE, computers

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High Integrity Global Precision Navigation Systems

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ABSTRACT

This paper will focus on the technology trends for (1) inertial sensors, (2) GPS accuracies, and (3) integrated GPS/INS systems, including considerations of jamming for military platforms and weapons, that will lead to the high integrity, one meter accuracy global precision navigation systems of the future. For inertial sensors, trend-setting sensor technologies applicable to military systems will be described. They are: fiber-optic gyros, silicon micromechanical gyros, resonating beam accelerometers, and silicon micromechanical accelerometers. A vision of the inertial sensor instrument field, and inertial systems for military applications for the next few decades will be given. GPS specified and observed current accuracies will be described, as well as, planned accuracy improvements due to various stages of the WAGE implementation, inter-satellite ranging, and "all-in-view" tracking. Uses of relative and differential GPS will be discussed. The trend towards tightly-coupled GPS/INS, where both code and carrier tracking loops are aided with inertial sensor information, will be described and the synergistic benefits explored. Some examples of the effects of jamming will be described and expected technology trends to improve system anti-jam capability will be presented.

1. INTRODUCTION

The current 16 meter (SEP) specified accuracy or 8 to 10 meter (CEP) observed accuracy of the Global Positioning System (GPS) Precise Positioning Service (PPS) provides impressive world-wide navigation performance especially when multiple GPS measurements are combined in a Kalman filter to update an inertial navigation system (INS) on a military platform or a weapon. The Kalman filter provides an opportunity to calibrate some of the GPS errors, such as clock and ephemeris errors, as well as several of the inertial system errors, and when properly implemented, CEP's better than 8 meters have been observed. In the next few decades accuracies in the integrated navigation solution will improve to, first, the 3 meter level (for precision strike type applications) and then possibly to the 1 meter level. These accuracies will need to be available in the face of hostile jamming of GPS, and the inertial system will provide autonomous navigation information during periods of GPS outage. This paper describes expected technology trends for inertial sensors in Section 2. Section 3 describes expected accuracy improvements and implementations for satellite navigation, and Section 4 discusses issues and benefits of GPS/INS integration particularly in a jamming environment. The combination of a robust, anti-jam GPS receiver and an accurate, low-cost inertial system provides the high integrity global precision navigation system of the future.

2. INERTIAL SENSOR TRENDS

Major changes are currently underway in technologies associated with inertial sensors used for stabilization, control, and navigation. These changes are enabling the proliferation of inertial sensors into a wide variety of new military and commercial applications. Inertial sensor manufacturers have begun to adopt many of the fabrication techniques that have been developed by the solid-state electronics industry over the last decade. Inertial sensors are being fabricated in silicon, quartz, and with electro-optic materials, such as lithium niobate, by employing low-labor-intensive batch processing techniques. The utilization of these techniques is resulting in low cost, high reliability, small size, and light weight for inertial sensors and for the systems into which they are integrated. Some inertial sensors have already been fabricated with dimensions so small that they are barely visible to the naked eye. Some of the more trend-setting emerging sensor technologies are described next. They are fiber-optic gyros, micromechanical gyros, resonating beam accelerometers, and micromechanical accelerometers. (Refs. 1, 2)

Fiber-Optic Gyros (FOG)

Sagnac effect rotation rate sensors result from the counter propagation of light beams in a waveguide which exhibits optical reciprocity between its clockwise and counterclockwise paths. Rotation normal to the waveguide plane upsets this symmetry, which is then photoelectronically detected and processed to provide an indication of rotation rate. The FOG is implemented using an integrated optics chip constructed in lithium niobate, and fiber-optic sensing coil (a few meters to a kilometer long), diode light source, and photodetectors. (see Fig. 1) This configuration is expected to be supplanted eventually by quantum well technology, such as gallium arsenide, which will then allow integration of most of the above components into a single substrate attached to the fiber-optic coil thus increasing reliability and reducing costs. FOG sensors have no gas or mirrors and do not exhibit lock-in at low rate, which are disadvantages associated with some ring laser gyros. They therefore should be an economical replacement for the ring laser gyro (RLG) providing the same level of gyro bias performance.

Silicon Micromechanical Gyros

Micromechanical gyros are usually designed as an electronically-driven resonator, often fabricated out of a single piece of quartz or silicon. Such gyros operate in accordance with the dynamic theory that when an angle

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rate is applied to a translating body, a Coriolis force is generated. When this angle rate is applied to the axis of a resonating tuning fork, its prongs receive a Coriolis force, which then produces torsional forces about the sensor's axis. These forces are proportional to the applied angle rate, which then can be measured capacitively (silicon) or piezoelectrically (quartz). The output is then demodulated, amplified, and digitized to form the device output. Silicon micromechanical instruments can be made by bulk micromachining (chemical etching) single crystal silicon or by surface micro-machining layers of polysilicon. Many manufacturers are developing gyros and accelerometers using this technology. Their extremely small size combined with the strength of silicon makes them ideal for very high acceleration applications.

Draper Laboratory has demonstrated a 30 degree/hour (°/h) open-loop silicon tuning fork gyroscope with folded beam suspension in which the flexured masses are electrostatically driven into resonance with a comb-like structure. (see Fig. 2) Rotation is sensed capacitively along the axis normal to the plane of vibration. The Draper gyroscope is aimed at the automobile market and is being marketed through an alliance with Rockwell International. Between 3,000 and 10,000 devices can be produced on a single five-inch silicon wafer. Devices with lower drift rates are being developed for more demanding applications, such as autopilot control and smart munitions.

Resonating Beam Accelerometers

Resonant accelerometers (sometimes referred to as vibrating beam accelerometers, VBAs) have a principle of operation that is similar to that of a violin. When the violin string is tightened, its frequency of operation goes up. Similarly when the accelerometer proof mass is loaded, one tine is put into tension and the other into compression. These tines are continually electrostatically excited at frequencies in the hundreds of kilohertz range when unloaded. As a result, when "g" loaded, one tine frequency increases while the other tine frequency decreases. This difference in frequency is a measure of the device's acceleration. This form of accelerometer is essentially an open loop device, in that, the proof mass is not rebalanced to its center position during the application of a force. For accuracy, it relies on the scale-factor stability inherent in the material properties of the proof mass supports. These accelerometers can be constructed using several different fabrication techniques. One method is to etch the entire device (proof mass, resonating tine, and support structure) from a single piece of quartz.(see Fig. 3) Using such techniques can result in low-cost, highly reliable accelerometers with a measurement accuracy of better than 100 micro g's (μg's). Constructing this accelerometer from a single piece of quartz results in high thermal stability, along with dynamic ranges approaching those obtainable in the timekeeping industry. Silicon micromechanical resonator accelerometers are also being developed.

Silicon Micromechanical Accelerometers

Micromechanical accelerometers are either the force rebalance type that use closed-loop capacitive sensing and electrostatic forcing, or the resonator type as described above. Draper's force rebalance micromechanical accelerometer is a typical example, in which the accelerometer is a monolithic silicon structure (i.e., no assembly of component parts) consisting of a torsional pendulum with capacitive readout and electrostatic torquer. (see Fig. 4) This device is about 300 x 600 micro meters (μm) in size. The pendulum is supported by a pair of flexure pivots, and the readout and torquing electrodes are built into the device beneath the tilt plate. The output of the angle sensor is integrated and then used to drive the torquer to maintain the tilt plate in a fixed nulled position. The torque required to maintain this balance is proportional to the input acceleration. Performance around 250 μg bias and 250 parts per million (ppm) of scale factor error have been achieved.

Future Technology Applications

Solid-state inertial sensors like those described previously have potentially significant cost, size, and weight advantages over conventional instruments, which will result in a rethinking of the options for which such devices can be used in systems. While there are many conventional military applications, there are also many newer applications that will emerge with the low cost and very small size inherent in such sensors, particularly at the lower performance end of the spectrum. In nearly every case, when these newer solid-state inertial technologies have been evaluated against today's technology, given comparable technical requirements, this new class of solid state inertial sensors becomes the winner because the basis of selection is almost always cost. A vision of the inertial instrument field for relevant military applications for the next twenty years is shown in Tables 1 and 2 for the gyro and accelerometer, respectively.

The performance application region of about 0.01°/h for gyros is expected to shift from current ring laser gyro applications to fiber optic gyros, which will detect their rate-induced Sagnac frequency shifts using lithium niobate or gallium arsenide technologies. The ring laser gyro is an excellent instrument, but its manufacturing is heavily dominated by precision machining processes and alignment requirements, which force its costs to remain relatively high. However, one particular area where the ring laser gyro is expected to retain its superiority is in the area of scale factor. The laser gyro has its optical path maintained in a rigid structure, whereas the fiber-optic gyro has its path in fiber, making the FOG fundamentally much more susceptible to environmental effects such as temperature changes. For comparable performance applications, the selection between the FOG and the RLG will very likely depend on the scale factor requirements (i.e., the accuracy in measuring an applied rotation rate).

The tactical low-performance end of the application spectrum will be dominated by micromechanical inertial sensors. These could be, for example, gyros and accelerometers photolithographically constructed in silicon or quartz and subsequently etched in very large numbers as a single batch. The military market will likely push the development of these sensors for applications such as "competent" and "smart" munitions, aircraft and missile autopilots, short time-of-flight tactical missile guidance, fire control systems, radar antenna motion compensation, "smart skins" utilizing embedded inertial sensors, multiple intelligent small projectiles such as flechettes or even "bullets," and wafer-scale GPS/inertial integrated systems.

The potential commercial market for micromechanical inertial sensors is orders of magnitude larger than any contemplated military market. The application of micromechanical gyro technology to the automobile industry is one case where, for example, a true skid detector requires a measure of inertial rate in order to operate successfully. Products designed for this industry must be inexpensive and reliable, both characteristics of solid-state technology. Many other micromechanical inertial sensor applications exist for automobiles such as airbags, braking, leveling, and GPS augmented navigation systems. Additional commercial applications can be found in products such as camcorders, factory automation, general aviation, and medical electronics. The performance of the micromechanical instruments will likely continue to improve as more commercial applications are found for this technology.

Since the end of the "Cold War", the actual number of military inertial systems that will be procured in the future has been uncertain. However, the general trend is clearly away from large strategic systems towards smaller tactical systems and towards military applications of commercial products. Table 3 gives some projections of cost for quantity production of future inertial systems. The systems are made up of gyros and accelerometers whose performance match the mission requirements. Current research and development activity for inertial sensors spans the spectrum of the four performance ranges shown. The United States Defense Advanced Research Projects Agency is pursuing the FOG based 0.01 °/h INS in its GPS Guidance Package (GGP), while many commercial firms are pursuing the mid to very low performance ranges in Table 3. Size has also become important. The GGP has a volume goal of 100 cubic inches, a weight goal of 7 lbs, and a power consumption goal of 25 watts. A Draper Laboratory system using micromechanical instruments and a GPS receiver is being developed with a volume requirement of 30 cubic inches, and a goal of 9 cubic inches. These latter two programs use GPS to update the navigation information and to calibrate the inertial component errors.

3. GLOBAL POSITIONING SYSTEM (GPS)

The specification that is currently applicable to the Global Positioning System results in a precise positioning of a GPS receiver operating with the P(Y) code of approximately 10 meters (CEP) in the WGS-84 coordinate system. Recent advances and planned programs to improve GPS accuracy, new approaches on how to use GPS in relative or differential modes, and new techniques to reduce target location error have all contributed to the real possibility of developing a "precision strike" 3 meter CEP system in the near-term and possibly, systems with 1 meter CEP in the far-term. This section will discuss these items.

GPS Specified Accuracies

The current 16 meter (SEP) specified accuracy,* or 8 to 10 meter (CEP) observed accuracy of the GPS PPS (Precise Positioning Service) provides impressive navigation performance especially when multiple GPS measurements are combined in a Kalman filter to update an INS on a weapon. The Kalman filter provides an opportunity to calibrate the GPS errors, as well as, the inertial errors, and when properly implemented, CEPs better than 8 meters have been obtained. For example, in 1993 the USAF dropped GPS/INS equipped GBU-15 bombs from F-16s and demonstrated better than 8 meter accuracy. (Ref. 3) Currently, some of the platforms and weapons in the US inventory exploiting (or planning to exploit) GPS/INS are listed in Table 4.

In assessing the accuracy of GPS, the largest error sources are in the space and control segment. Ionospheric errors, tropospheric errors, satellite clock errors, and satellite ephemeris errors are the dominate error contributors. For most military receivers, the ionospheric errors can be reduced by using a two frequency receiver and tropospheric errors can be reduced by using a deterministic compensation model. Table 5 gives a typical absolute GPS error budget (Ref. 4, p. 68). The errors due to satellite clock and ephemeris can be decreased by either of 3 methods: Wide Area GPS Enhancements (WAGE), differential GPS (DGPS), or relative GPS (RGPS). The next three subsections describe these approaches that offer potential for "precision strike accuracy."

Wide Area GPS Enhancements (WAGE)

The GPS ground control segment is responsible for determining the ephemeris and satellite clock parameters and uploading them to each satellite once a day. During that following day, the errors in the satellite's position and time, as a function of time, slowly grow from the corrected information. Figure 5 illustrates clock error growth. (Ref. 5) In the current GPS constellation, the satellite clock and ephemeris errors have been observed to be on the order of 3.4 and 1.4 meters (1σ), respectively. (Ref. 4, p.99) Combining these errors with the atmospheric residual error of 0.2m in Table 5 by taking a root sum square gives a user range error (URE) of about 3.7 meters.

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* The method of expressing navigation accuracy for NATO systems is the metric ninety-five percent probable error. Using this means to specify current generation, military navigation satellite receiver accuracy yields horizontal and vertical accuracies of 20 and 30 meters, respectively.

If it is assumed that receiver and other independent random errors are approximately 0.7m (1σ), denoted as UEE, then the total user equivalent range error (UERE) is

$$\text{UERE} = \text{SQRT}\ (\text{URE}^2 + \text{UEE}^2)$$

For the values of URE and UEE specified above, UERE is 3.8m (1σ).

Horizontal dilution of precision (HDOP) is a geometrical factor that is a function of the geometry between the GPS receiver and the tracked satellites. For tracking 4 satellites, HDOP is typically 1.5 . Then applying the approximate formula

$$\text{CEP} = (0.83)(\text{HDOP})(\text{UERE})$$

results in a CEP of 4.7 meters for the present satellite upload approach. (Note that further calculations are required for a weapon diving towards a target such that the projection of vertical errors is also included.)

An innovative and extremely simple strategy was developed in 1994 for accuracy improvements in the once a day correction updates (Ref. 5) and experiments were conducted to verify the concept. (Ref. 6) The experiment involved uploading pseudorange corrections for all satellites with each scheduled, individual satellite upload. The correction tables are available to all authorized users in the encrypted navigation message. A receiver can decode the messages from all satellites it is tracking, to find and apply the most recent table to correct these satellites. The GPS message table of corrections is repeated every 12.5 minutes; the time that the table was updated is broadcast every 30 seconds. So a user can rapidly find out which satellite in his field-of-view contains the most recent table of corrections. Once that is found, the user selects the corrections for the satellites that are being tracked. In this scheme, the expected error contributions from satellite clock and ephemeris are expected to be about 1.8m (1σ) or better. This is the case of tracking 4 satellites, where the average age of the correction data is now 4.8 hours, as opposed to an average age of 12 hours in a once a day upload. Repeating the previous calculation with URE of 1.81 meters and UEE of 0.7 meters results in a UERE of 1.94m and a CEP of 2.4 meters. Actual experiments reported (Ref. 6) indicate an improvement of 7.5 meters to 2.5 meters in CEP and 9 meters to 3.25 meters in SEP for a stationary GPS receiver.

The average age of the data improves if more than 4 satellites are tracked. If tracking 7 satellites, the average age is 3 hours; if tracking 8, the average age is 2.67 hours. (Ref. 5) Tracking more than 4 satellites also improves HDOP. For 8 satellites, HDOP is typically 1. The theoretical calculation now gives a CEP of 1.6m. With multiple GPS measurements used in a Kalman filter and an INS, even higher accuracy should be achievable.

At the time this paper was written, the GPS Joint Program Office has not finalized the final implementation details on WAGE, but expectations are that it will be implemented. Even further improvements are contemplated to clock and ephemeris accuracy. (Ref. 4, p.102). In this later phase, the data from five Defense Mapping Agency (DMA) GPS monitoring sites will be integrated with data from the existing Air Force operational control segment. By including additional data from the DMA sites, which are located at higher latitudes than the Air Force sites, an additional 15 percent improvement in combined clock and ephemeris accuracy could be anticipated. Improvements to the Kalman filter that is used in the ground control segment to process all the satellite tracking information can be expected to further reduce the errors by 15% and by incorporating more dynamical models in the filter, another 5% improvement may be anticipated. Table 6 summarizes these improvements (Ref. 4, p. 102) Thus, an UERE on the order of 1.4 meters is a reasonable possibility with the atmospheric residual unchanged. With all-in-view tracking, and multiple GPS measurements combined with an inertial system, CEPs on the order of 1 meter appear quite possible in the next few decades.

Block IIR and Block IIF GPS satellites to be used in the next century will have the capability for inter-satellite autonomous ranging and communications (Ref. 4, p.109). The precise ranging information would provide further accuracy improvements or replace some of the previously mentioned approaches. Satellites will be able to update their own time and position using crosslinks as often as every 15 minutes. The use of a communications link would be used to improve GPS signal integrity for all users. If an anomalous signal was detected at a monitoring station, commands and information could be broadcast to all satellites immediately, and therefore, also to users.

Differential GPS (DGPS)

DGPS typically uses a single reference receiver located at a surveyed point to compare its range measurements to the GPS satellites with those calculated from the surveyed location. The differences between the measured and calculated ranges are the pseudorange corrections that are transmitted to other user-receivers. The corrections remove most of the satellite clock and ephemeris errors as well as ionospheric and tropospheric delay errors. The corrections are usually very accurate over a few hundred miles, particularly if the weapon (or aircraft) has its own tropospheric and ionospheric corrections. In 1995, six GBU-15s incorporating a differentially corrected INS/GPS navigation scheme, were dropped from US Air Force F-16s at Eglin AFB. These tests demonstrated that better than 5 meter CEP was achieved. (Refs. 7, 8)

In actual implementation in a theater of operations, corrections would be sent over encrypted data links to the aircraft (or weapon) in a timely fashion. Accuracy of these corrections would be a function of distance to the ground reference stations and time since the last update to the weapon. The cost of the improved accuracy is the increased vulnerability of the data links, as well as, the ground stations and aircraft equipment needed to support the implementation. This concept could use the WAGE

technique for transmission of corrections; i.e., broadcast the corrections via the satellites. (Ref. 9 contains additional discussion on these options.)

Relative GPS (RGPS)

Relative GPS is similar to both DGPS and WAGE in that the concept owes its increased accuracy to the elimination of "bias like" errors due to ephemeris and satellite clock errors. However, these errors are not explicitly calculated and corrected for, as in WAGE and DGPS. In RGPS, two GPS receivers are forced to track the same satellites and (conceptually), the difference between the two receivers (the relative navigation solution) only contains small random noise errors since the "bias-like" large contributors to the navigation error cancel out.

RGPS is probably the least known of the 3 concepts proposed to achieve high accuracy. Experiments have also been conducted to show that 3m (CEP) is possible. In Reference 10, the RGPS concepts and experimental results are described. RGPS is similar to DGPS in that a data link for the transfer of information is typically required if using ground-based receivers. However, as explained in Reference 10, RGPS has certain attributes when targeting is considered. If aircraft on-board targeting of the weapon is performed, then the target location is identified relative to the aircraft GPS/INS set and those relative coordinates are loaded into the GPS/INS guided weapon and the weapon is made to guide to the target location using the same set of satellites that the aircraft used. In this manner, the biases due to satellite clock and ephemeris errors partially cancel out of the solution.

Summary of GPS Approaches

This section described 3 approaches involving GPS that could be used to update an INS for high accuracy applications. WAGE, DGPS, and RGPS all have the potential to provide updates accurate enough for high accuracy in a non-jamming environment. The next section of the report will describe trends in GPS/INS integration and discuss GPS jamming issues.

4. GPS/INS INTEGRATION

Many military inertial navigation systems could be replaced with less accurate inertial systems if GPS were continuously available to update the inertial system to limit its error growth. A less accurate inertial system usually means a less costly system. However, given the uncertainty in the continuous availability of GPS in most military scenarios, an alternate way to reduce the avionics system cost should be to attack the cost issue directly by developing lower cost inertial sensors while maintaining their current accuracy and low-noise levels as reported in Section 2. For applications without a jamming threat, GPS updating is expected to eventually provide much better than 3 meter navigation accuracy (CEP) when used in conjunction with an INS. In this section, the benefits and issues in using inertial navigation systems augmented with GPS updates are reviewed including a discussion of jamming issues.

Benefits/Issues of GPS Aided Inertial Systems

The synergism offered by GPS/INS integration is outlined in the following 3 paragraphs:

(1.) Aiding the receiver's carrier and code tracking loops with inertial sensor information allows the effective bandwidth of these loops to be reduced, even in the presence of severe vehicle maneuvers, thereby improving the ability to track signals in a noisy environment such as caused by a jammer. The more accurate the inertial information, the narrower the loops can be designed. In a jamming environment, this allows the vehicle to more closely approach a jammer-protected target before losing GPS tracking. A factor of 3 to 4 improvement in approach distance is typical. Even outside a jamming environment, INS data provides a "smooth" and accurate navigation solution in situations where GPS receiver navigation solutions alone would be subject to short-term outages caused by geometry, signal-strength variations, and antenna shading.

(2.)The inertial system provides the only navigation information when the GPS signal is not available. Then inertial position and velocity information can reduce the search time required to reacquire the GPS signals after an outage and to enable direct P(Y) code reacquisition in a jamming environment.

(3.) Low-noise inertial sensors can have their bias errors calibrated during the mission by using GPS measurements in a "tightly-coupled" navigation filter that combines inertial system and GPS measurements to further improve the benefits listed under (1) and (2). The accuracy achieved by the combined GPS/INS system should exceed the specified Precise Positioning Service accuracy of GPS alone.

The synergistic benefits of combining inertial data with GPS data as described in the previous paragraph are notionally shown in Figure 6.

However, the ability to adequately calibrate the biases in low-noise inertial system components depends on the avionics system architecture. There are two different system architectures that have been commonly implemented to combine the GPS receiver outputs and the inertial navigation system information and thus obtain inertial sensor calibration and to estimate the vehicle state. They are referred to here as the "cascaded filter" and the "tightly-coupled" approaches. It is generally expected that a tightly-coupled filter implementation would result in better inertial system calibration and better CEP. The reasons for that expectation will now be explained.

In the typical cascaded filter approach, as shown in Figure 7, there are two separate Kalman filters in the GPS/INS system. The first is within the GPS receiver. The GPS receiver loops can be aided with information

from the inertial system, and the receiver outputs position and velocity data from its own Kalman filter. The receiver's Kalman filter is usually not optimized for the vehicle dynamics or for the errors in the inertial system aiding it. Furthermore, its position and velocity errors are potentially correlated in time with the inertial errors. The second Kalman filter that compares the receiver position and velocity outputs with those of the inertial system is usually run at a much lower rate (typically 5 to 10 seconds update interval) than the receiver filter (10 to 1 Hz). This is to avoid possible filter instability because the second filter is designed as if the errors in its input measurements were uncorrelated. (Ref. 11)

In the tightly coupled approach, shown in Figure 8 there is only one Kalman filter. The GPS measurements of pseudorange and deltarange as derived from the code and carrier tracking loops are treated as measurement inputs in a single Kalman filter that also includes the INS error states. The measurements are typically processed at a 1 Hz rate. One single, overall optimal filter in the tightly-coupled approach will provide more accurate estimates than two cascaded filters operating at a lower update rate. Incorporating measurements much more frequently will contribute to faster calibration of the inertial sensors.

Tightly coupled implementations are also more robust against jamming in that the cascaded filter usually cannot provide a GPS update to the inertial system if fewer than four satellites are being tracked by the receiver. The receiver navigation solution degrades and begins to track the inertial system errors. The tightly-coupled system, however, can make use of measurements of pseudo-range from three, two, or just one satellite. This could be extremely beneficial in a jamming scenario especially if large areas of the sky are blanked out by a nulling antenna and only a few satellites are available for tracking. This capability is also particularly important for utilization by marine ground forces and in low-level aerial applications. These applications impose severe signal masking restrictions due to foliage, terrain, and urban structures. Figure 9 shows expected results for different aiding system architectures and inertial system quality.

The trend during the last several decades in the design of multisensor navigation systems has been to use one centralized Kalman filter that uses raw measurement information from all available sensors (e.g., Doppler radar, synthetic aperture radar, GPS receiver, and other sources). Implementation of the tightly-coupled architecture allows for the straightforward inclusion of additional sensors or upgrades of existing sensors. Tightly-coupled systems should be implemented in many applications even in the presence of contemplated, improved receiver security features, such as GRAM/SAASM*, which may limit the availability of pseudorange and deltarange measurements outside the security boundary of the receiver. In this case, the security boundaries will have to be appropriately defined.

* GPS Receiver Applications Module/Selective Availability Anti-Spoofing Module (GRAM/SAASM)

Having now reviewed some of the main issues in GPS aiding of inertial systems, the next subsection will discuss jamming issues.

GPS/INS Jamming Issues

In designing an integrated GPS/INS trade-offs must be made between the use of an high accuracy inertial system and the use of a GPS receiver/antenna with high anti-jam (A/J) capability. Most military systems cannot afford to have both. The trade-offs to be made are a function of the phases of the scenario: GPS satellite acquisition, mid-course, and terminal. The presence of jamming in any of these phases presents a unique problem for that phase.

Proponents of high accuracy inertial systems will generally argue that a high A/J GPS is not required while GPS proponents will argue that use of a higher GPS A/J set will substantially reduce inertial system accuracy requirements. The arguments given by both are entirely dependent on the usually ill-defined mission and jamming scenario. However, what has generally become accepted is that the GPS is remarkably vulnerable to jamming during the C/A code acquisition phase where conventional receiver technology has only limited jammer tolerability (J/S - 27 dB). (Refs. 12, 13, 14) A one watt (ERP) continuous wave narrow-band, (CW) jammer located at 100 km from the GPS antenna terminals could prevent acquisition of any satellites. Figure 10 is very useful in determining trade-offs between required anti-jam margin and jammer power. A one watt jammer is "cheap" and the size of a hockey puck. Figure 11 shows some jammers. Furthermore, the C/A code can be spoofed by an even smaller power jammer. So generally, a GPS receiver cannot be expected to acquire the C/A code in a hostile environment. For long range cruise missile type applications, the C/A code could be acquired outside hostile territory and then the receiver would transition to P(Y) code lock which has a higher level of jamming immunity. A 1000 watt (ERP) jammer at about 100 km would now be required to break receiver lock. This is also not a difficult power-level for a jammer to achieve. Furthermore, as the weapon approaches the jammer, jammer power levels of about 10 watts would be effective in breaking P(Y) code lock at 10 km.

The P(Y) code has more anti-jam protection than the C/A code due to its ten times larger spread spectrum bandwidth. Therefore it is important to develop receivers that acquire the P(Y) code without having to acquire the C/A code. Current receiver technology during a direct P(Y) code acquisition would have a jammer tolerability of J/S of 31 to 35 dB.** However because the P(Y) code is very long, much time or many correlators would be needed for a two-dimensional search over code timing and Doppler frequency. It would be faster if satellite ephemerides and accurate code timing were available to

** P(Y) on frequency L1 is 3 dB lower in signal power than C/A on L1. P(Y) on L2 is 6 dB lower in signal power than C/A on L1. Hence, the A/J advantage (all other things being equal) of P(Y) acquisition is 4 to 7 dB better than C/A acquisition.

perform a "hot start." For a GPS aided weapon, accurate timing and satellite position could be transferred from the aircraft to the weapon. This transfer normally requires a wide-band data bus; few aircraft are so equipped.

As new receiver technology with massively parallel correlators, improved algorithms, and adaptive or nulling antenna technologies are incorporated into the system increasing its A/J capability, A/J performance will improve significantly. Some possibilities are illustrated in Figure 12. (Ref. 14) If A/J performance is doubled (in decibels), then the jammer in the previous cases would have to be many orders of magnitude larger to be effective at the same ranges mentioned. Such a large jammer would present an inviting target to an anti-radiation, homing missile. In the terminal area of flight against a target, the receiver will probably still be jammed and the vehicle will have to depend on inertial-only guidance or the use of a target sensor. Thus, it is important to make sure that adequate back-up vehicle guidance and navigation capability is provided to meet military mission requirements against adversaries who are willing to invest in electronic counter-measures. This fact is true today and is expected to remain so in the foreseeable future.

To prevent the use of the C/A code of GPS by hostile forces, it is necessary to jam the C/A code in the battlefield area, thus giving more emphasis to the need for our own forces to be able to acquire P(Y) code directly without using the C/A code. Additionally, a hostile force using differential GPS to improve accuracy is vulnerable to jamming of the data links that broadcast the corrections to users and to destruction of the differential ground stations.

In summary, the following militarily driven developments will be accomplished in the near future to improve anti-jam performance of military systems:

1. Lower cost but accurate inertial systems using new technologies such as micromechanical inertial instruments and fiber optic gyros.

2. Highly integrated, tightly-coupled GPS/INS system architectures.

3. Direct P(Y) code acquisition through improved interfaces to munitions, miniature on-board accurate clocks, and multiple correlators.

4. Higher performance, lower cost adaptive antennas using digital beam forming and modern algorithms.

5. CONCLUDING REMARKS

Recent progress in INS/GPS technology has accelerated the potential use of these integrated systems, while awareness has also increased concerning vulnerabilities to ECM. In the next decade, improvements in accuracy in the GPS signals will evolve to 1 meter due to planned programs by the GPS Joint Program Office. Many uses will be found for this high accuracy. In parallel, lower cost inertial components will be developed and they will also have improved accuracy. Tightly integrated, embedded, high anti-jam architectures for GPS/INS systems will become common replacing avionics architectures based on functional black-boxes where receivers and inertial systems are treated as stand-alone systems. Classified techniques will be developed to deny the use of GPS or GLONASS by hostile forces.

ACKNOWLEDGMENT

Thanks to Dr. Neil Barbour for assistance with the section on Inertial Sensor Trends.

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Future Navigation Application	Gyro Stability Requirement (°/h) 1σ	Typical Gyro Types Used
Cruise Missiles and Aircraft Navigation Systems	0.01 - 0.1	Fiber Optic Gyro Ring Laser Gyro
Tactical Missiles	0.1 - 10	Fiber Optic or Silicon Micromechanical Gyro
Flight Controls, Smart Munitions	Greater than 10	Silicon Micromechanical Gyro

Table 1 Future Gyro Requirements vs. Applications

Future Navigation Application	Accelerometer Stability Requirement (μg) 1σ	Typical Accelerometer Types Used
Cruise Missiles and Aircraft Navigation Systems	10 - 100	Quartz resonant or Silicon Micromechanical Accel
Tactical Missiles	100 - 1000	Quartz resonant or Silicon Micromechanical Accel
Flight Controls, Smart Munitions	Greater than 1000	Silicon Micromechanical Accel

Table 2 Future Accelerometer Requirements vs. Applications

	Flight Controls, Smart Munitions	Tactical Missiles	Tactical Missiles	Cruise Missiles, Aircraft INS
Accelerometer Technology	Silicon Micromechanical	Quartz Resonant or Silicon Micromechanical	Quartz Resonant or Silicon Micromechanical	Quartz Resonant or Silicon Micromechanical
Accelerometer Bias Stability (μg) 1σ	1000	200	100	50
Type of Gyro Technology	Silicon Micromechanical	Silicon Micromechanical or Fiber Optic Gyro	Fiber Optic Gyro	Fiber Optic Gyro
Gyro Bias Stability (°/h) 1σ	10	1	0.1	0.01
Future INS Production Cost	$500	$2,000	$10,000	$15,000

Table 3 Future INS Error Budgets (1σ) and costs

Platform or Weapon
Stand-off Land Attack Missile (SLAM) Tomahawk Block III Cruise Missile (TLAM-III) Tomahawk Block IV Cruise Missile (TLAM-IV) Joint Direct Attack Munition (JDAM) Joint Stand-off Weapon (JSOW) GBU-15 Precision Glide Bomb AGM-30 (Powered version of GBU-15) ATACMS Ballistic Missile Conventional Air Launched Cruise Missile (ALCM-C) Aircraft: B-1B, B-2, F-15E, F-16, F-18, F-117, F-22

Table 4 Platforms and Weapons Exploiting GPS/INS

GPS Noise-like Range Errors	1σ Values (meters)
Multipath	0.6
Receiver noise	0.3
RMS noise-like error	0.7
GPS Bias-like Range Errors	**1σ Values (meters)**
Satellite ephemeris	1.4
Satellite clock	3.4
Atmospheric residual	0.2
RMS bias-like error	3.7
Total absolute horizontal GPS rms error: $(0.7^2+3.7^2)^{1/2}$(HDOP) = 5.7m for HDOP =1.5. CEP = 4.7m	

Table 5 "Typical" Absolute GPS Error Budget

Enhancement	Anticipated Combined Clock and Ephemeris Error Improvement over Existing Combined Error of 3.6 meters (1σ)
Correction Updates (50% reduction)	1.8 meters
Additional Monitor Stations (Additional 15% reduction)	1.5 meters
Non-partioned Kalman Filter (additional 15% reduction)	1.3 meters
Improved Dynamic Model (additional 5% reduction)	1.2 meters

Table 6 Reduction of Combined Clock and Ephemeris Errors

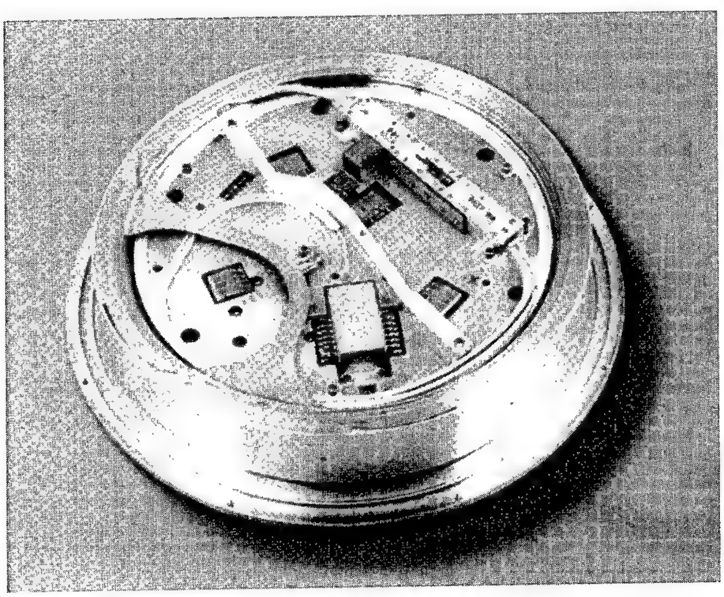

Figure 1 Fiber Optic Gyro

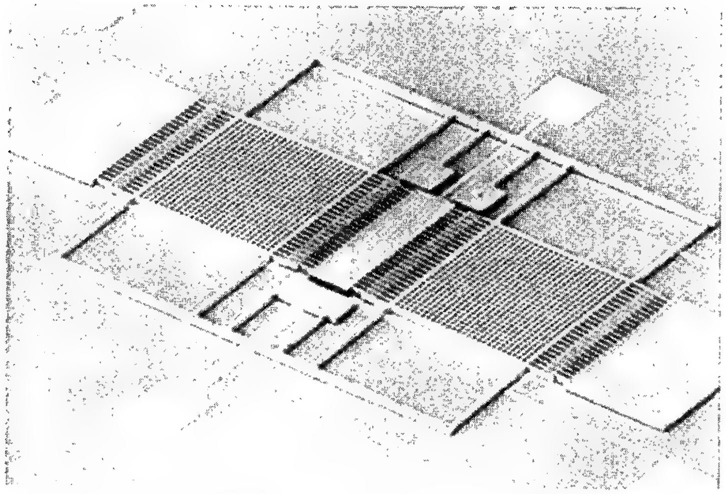

Figure 2 Micromechanical Tuning Fork Gyro

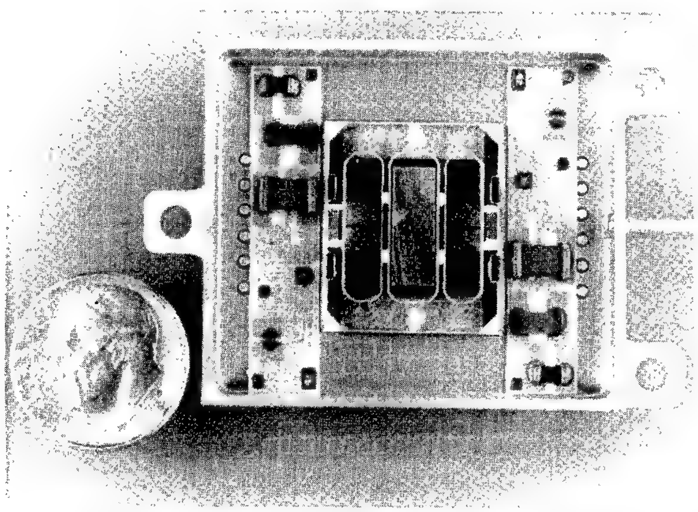

Figure 3 Quartz Resonant Accelerometer

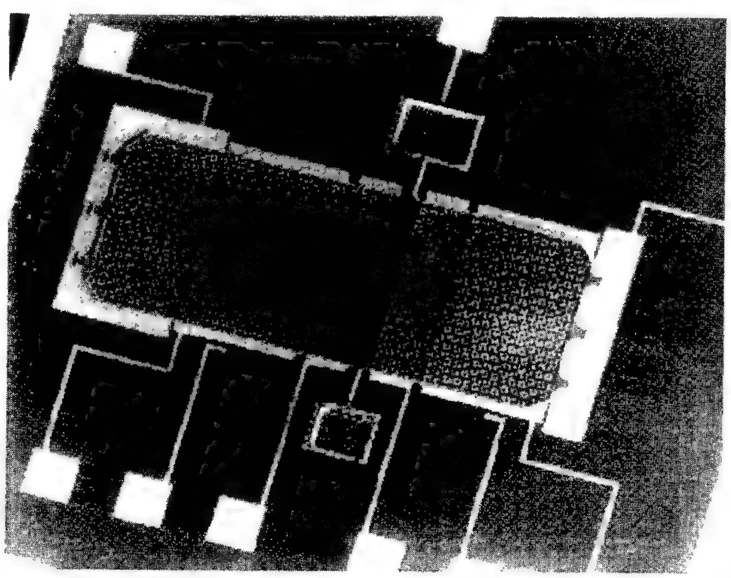

Figure 4 Micromechanical Pendulous Rebalance Accelerometer

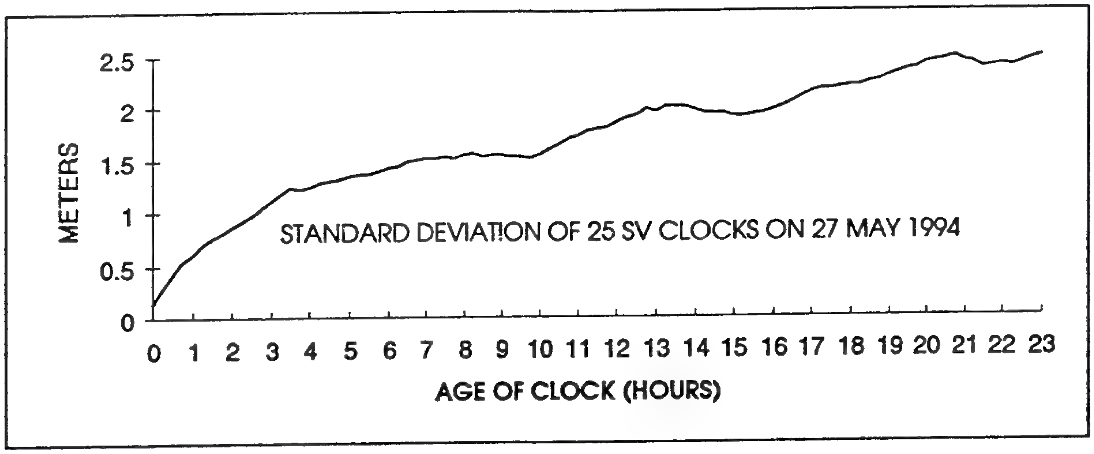

Figure 5 Clock Errors vs. Time

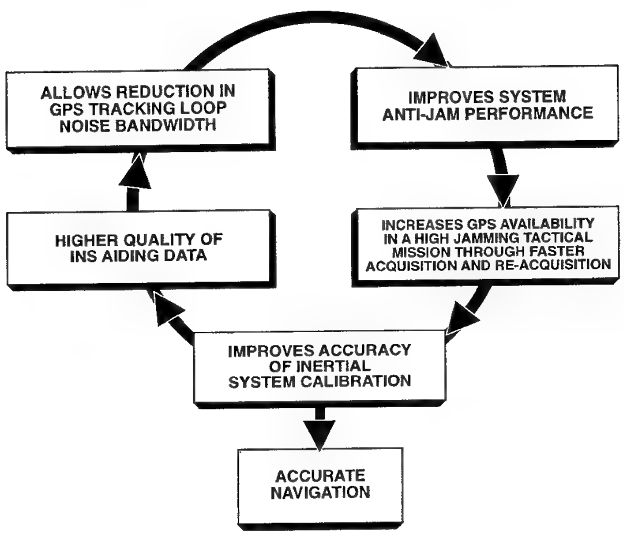

Figure 6 The Synergy of GPS/INS Integration

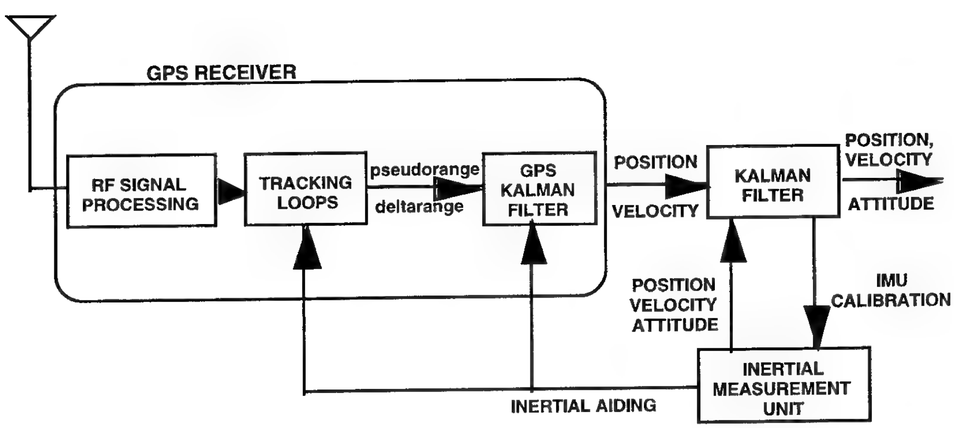

Figure 7 Cascaded Filter Approach

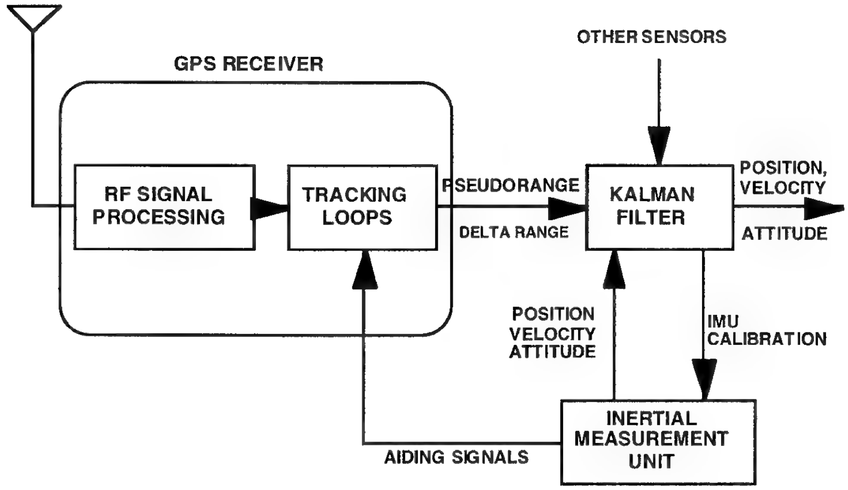

Figure 8 Tightly Coupled Approach

	Case 1 INS Flight Controls, Smart Munitions	Case 2 INS Tactical Missiles	Case 3 INS Cruise Missiles, Aircraft INS
Accelerometer Bias Stability (micro g's) - 1σ	1000	200	50
Gyro Bias Stability (deg/hr)- 1σ	10	1	0.01

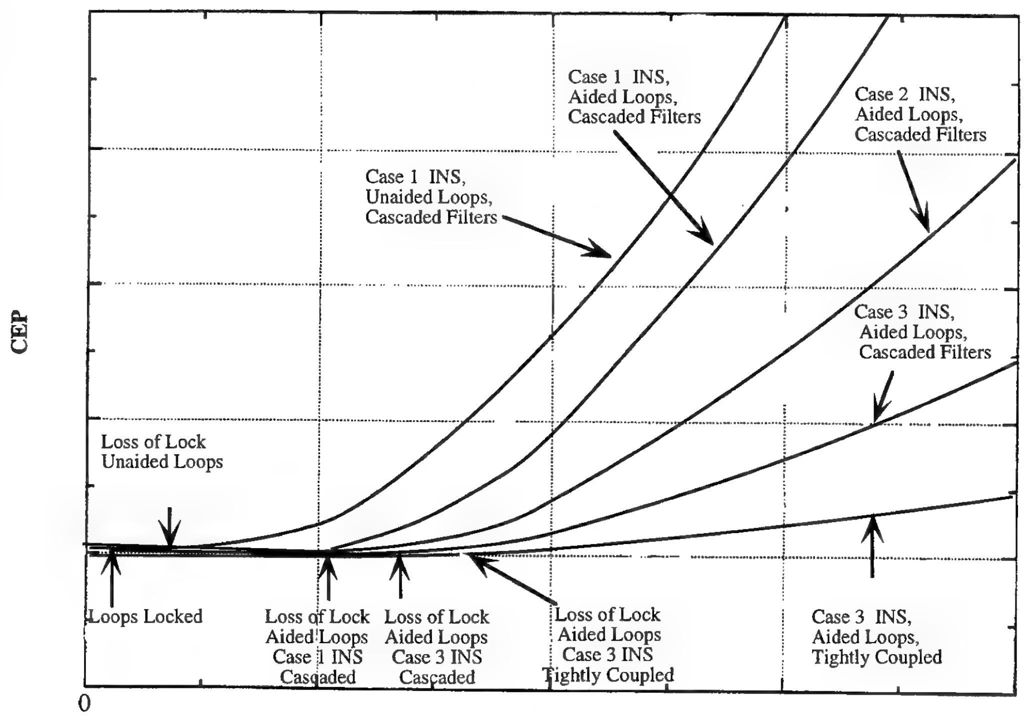

Figure 9 Benefits of Inertial Aiding/System Architecture with Jamming

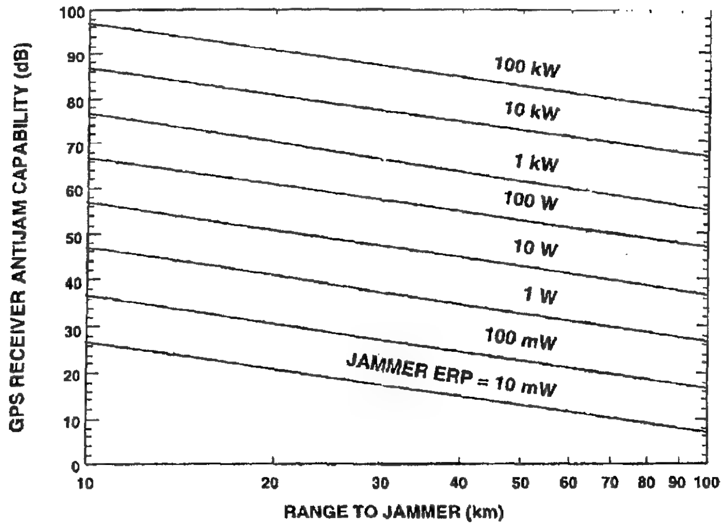

Figure 10 GPS Jamming Calculations

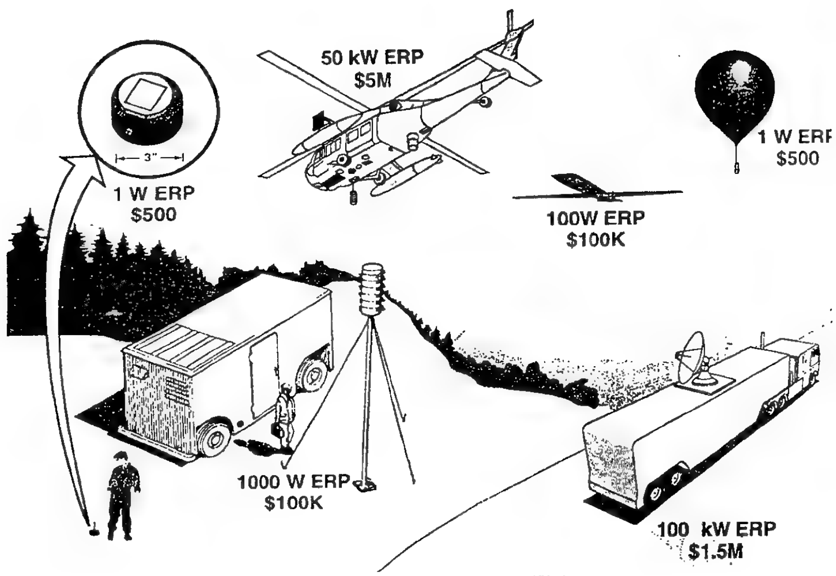

Figure 11 Jammer Possibilities

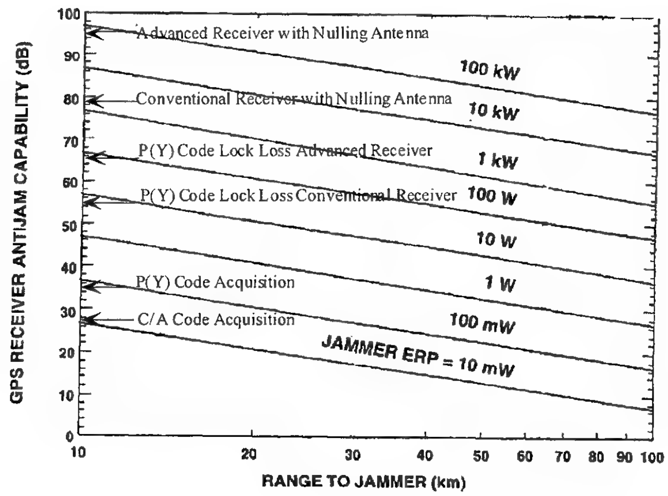

Figure 12 Possible A/J Capabilities

PAPER: B-16

DISCUSSOR'S NAME: E. Van Lil

QUESTION:

- Does the accuracy claimed include the effects of atmosphere (troposphere and ionosphere)?

AUTHOR/PRESENTER'S REPLY:

For current systems, the inaccuracy of atmospheric modeling/measurement is a small error in military systems using L1 and L2. For future systems, as other errors are reduced, atmospheric effects will become a dominant error. It may be possible to reduce those errors in "differential" systems but at a price.

PAPER: B-16

DISCUSSOR'S NAME: E. Schweicher

QUESTION:

Could you compare the evolution in the future of GPS and of the Russian system GLONASS?

AUTHOR/PRESENTER'S REPLY:

In my opinion, the future of GLONASS is directly related to the future economic conditions in Russia. The US is spending nearly 1 billion dollars per year to maintain and upgrade GPS for the future. It is unlikely that the Russians can afford to do that with GLONASS, so my opinion is that GLONASS will always be considered an experimental system and never achieve truly operational, reliable status.

DISCUSSOR'S NAME: C. McMillan

QUESTION:

1) Were the jammers discussed noise jammers?

2) Would you care to say anything about the vulnerability to coherent jammers?

AUTHOR/PRESENTER'S REPLY:

1) Yes.

2) For the discussion in this paper, it really doesn't matter which kind we are discussing.

Impact of New information Technology and Micro-Techniques on Avionics Functions and Structures

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SUMMARY

The avionics functions of the 70s and 80s had a growth rate of their embedded processing resources consistent with the progress pace of the semi-conductors technology.
The avionics functions designed in the early 90's were impacted by information technology, LCC and availability requirements; they are enlightened by the shift from federated to integrated avionics architectures.
The micro-techniques, which allow to combine analog sensing and/ or actuating with local processing and communication resources, combined to the new trends of information technology in networks (client/ server architectures), and the steady increase of semi-conductors technology, may initiate the move of the integrated avionics functions to the distributed micro-systems.
These micro-techniques and their application fields are briefly described and their impacts on the architecture and functions are estimated. Some results come from advanced development of the Radar of the next generation, based on Active Array Antenna. Preliminary conclusions are that commercial technology (COTS, Software tools, digital processing, communication protocols) will be usable; an aggregated ***increase of the communication requirements*** has to be expected from the distribution of the sensors all over the platform but placing the boundaries at the wrong place while distributing the system may actually ***worsen the communication issues***, as some management and fusion/ consolidation processing resources will have to remain centralized, notwithstanding potential exchanges between the distributed elements.

These communication constraints, together with the cooling and power supply distribution issues, remain challenges that the avionics community would have to solve by itself.

1. INTRODUCTION

The avionics functions and structures (architectures) are influenced by operational requirements, semi-conductors technology state-of-the art, information technology evolutions, amongst other drivers. The emergence of micro-systems backed-up by micro-techniques (the art of combining sensing / actuating / processing and communication resources on the same chip) is an enabling technology which may induce major changes and provide improved operational capabilities.
The aim of this paper is to build some perspective on the impact of the progress in the fields of semi-conductors technology, information technology and micro-techniques on the avionics functions and architectures, and to derive some advantages and issues. An operational function (detection) is given as an example requirement for its implementation in the year 2020 time-range.

2. THE EXAMPLE REQUIREMENTS

The "detection function" of a future combat aircraft is in charge of acquisition and processing of signals, data and information to have the best possible knowledge of the current environment.

It results of the association of a priori knowledge, on board and off board sensors. The a priori knowledge is contained in the aircraft database, the mission plan fed in before take-off, and the situation update which could be received during the flight.

The off-board sensors could be surveillance systems of various types, reconnaissance asset or sensors of the other combat aircraft in the same strike package.

A priori knowledge and off-board sensor data are delivered by communication means.
On board sensors could be passive or active. They should have a full spherical field of view and have all weather capabilities.

On board sensors are tasked to gather data of various types to establish for example Air threat, ground/surface threat, to perform target acquisition and tracking.

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 2.

Due to physical and design constraints, the sensing elements, or collectors, are located in a limited number of places on the platform and they should be shared by the different tasks.

3. EXISTING AND MID-TERM ARCHITECTURES

3.1 Current state-of-the-art of In-service Architectures

Most of the currently operating platforms are using federated architectures for their avionics systems. Each sensor contains its own processing suite (Signal, Data and Information processing) and doesn't usually share any resource (analog / digital / cooling / supply) with other sensors. The advantages and drawbacks of these architectures have been discussed in many papers. In the light of the future micro-systems on a chip, they appear as coarse grain heterogeneously distributed systems, from which some lessons should not be forgotten, mainly regarding communication (networks) aspects.

3.2 Medium Term State-of-the Art

Several programs are concerned by Modular Integrated Avionics, where standardization, resource sharing, reconfiguration, fault-tolerance are aimed at, from apertures to analog, signal, data/information processing, and communications (networks) :

- ASAAC
- EUCLID CEPA 4
- F22
- JAST / JSF
- JIAWG
- PAVE-PACE

The MIA approach promotes integration and resource sharing of avionics functions inside domains (e.g. sharing apertures, sharing RF modules, sharing digital processing between Radar, EWS, CNI,...). This leads to physical clustering where information fusion, resource reconfiguration, cooperation across functions will be improved from the federated approach. MIA has to be regarded as an "horizontal integration".

4. ARCHITECTURE DRIVERS FOR 2020

4.1 Semi-conductors

According to Moore's law, a multiplying factor close to 100 000 in digital processing performance could be expected between today state-of-the-art and 2020 one, provided the market allows for the industrial investment (Rock's law). Physical limits may also dictate some slow-down in the progress pace, and trade-off may dictate to accept lower complexity and functionalities to limit the power dissipation. A conservative forecast could nevertheless let expect chips offering hundreds of GOPs and gigabytes of storage capacity.

The question is : will it be sufficient ?

The embedded processing resources of major avionics equipment have been measured over the past 20 years for a couple of fighter aircraft and a multiplying factor of roughly 17 between each generation (10 years period) was observed.

This figure is consistent with the progress pace of the semi-conductors technology which provide a doubling of performances (brute force) every 18 months, corresponding to a factor 64 over 10 years.

For the Radar of the next generation, based on Active Array Antenna, the estimated multiplying factor is in the range of 30 to 100.

For micro-systems, they will have the advantage to carry a major part of the required processing resources.

4.2 Information Technology

One of the trends which seems the most promising is the association of Object oriented technologies and networking architectures fueled by a worldwide effort of major software companies around the Internet/ Intranet. The ability to exchange information through a user transparent routing (including wireless communication) is one of the requirements of the example function.

4.3 Micro-techniques

Called MST -MicroSystems Technology- in Europe and MEMS -MicroElectroMechanical Systems- in USA, they combine electronics, mechanical, optical technologies to provide complete on chip intelligent chain including sensors and actuators.

The current micro-sensors are silicon or quartz machined with patterns in the millimeter range. Forecasting in this area may prove more hazardous, but micro-machining in the micron to millimeter range can be foreseen and should promise cheap mass production and affordable high count applications.

4.3.1 Micro-sensors

Micro-techniques are expected to deliver micro-sensors for every kind of physical input :

- pressure
- temperature
- RF spectrum
- Optical spectrum
- Infra-red spectrum
- ....

The common characteristics is that they will combine sensing elements (transducer) with analog processing, digital processing and communication (preferably optical).

This generic structure will be considered for estimating their impact on architectures and function

4.3.2 Micro-actuator

This domain will cover mainly mechanical output , but RF transmitter, Laser emitter, ...should be placed in this classification.

Micro-actuator are expected to have the same type of generic structure as that of micro-sensors

4.4 Impact of drivers on architecture

Introducing micro-techniques in future systems would impact their architectures as follows :

- higher number of individual sensing / actuating elements
- closer integration of sensor signal processing, control algorithms, actuator command circuits
- distributed processing structures and associated (safe) communications links
- multi-level fault-tolerance : from micro-systems to sub-systems to global system. The local intelligence will improve the sensor integrity assessment, which will be mandatory in case of poor accessibility to the individual micro-systems .

As formerly written, the following derived potential architecture is not intended at a particular sensor; it is proposed as a generic approach, regardless of the type of micro-system used (except for the case of the control structure, which is based on an advanced work on an Active Array Antenna).

5. POTENTIAL ARCHITECTURE

The aircraft avionics system, which will be an integrated system (MIA) in the 2005 time-range state-of-the-art, may evolve towards a distributed architecture of micro-systems and thus will rely more heavily on communication resources for performing a logical integration rather than a spatial one; this will offer the added benefit of better battle damage resistance capability.

5.1 Potential change on the processing structure

Micro-systems are expected to merge analog and digital circuits on the same chip, or at least the same substrate, so as to provide a complete function ("vertical" integration, versus "domain" or "horizontal" integration).

If it is very likely to have the signal processing part close to the sensor, one may question about the location of the data processing; wherever no cooperation or fusion with sensing neighbor is needed, the complete digital processing chain may be vertically integrated. As soon as some synthesis must be made from all the pre-processed data delivered by the distributed sensors, a choice has to be made between a central manager connected to all sensors, and a distribution of partial results across all sensors

5.2 Potential change on the communication structure

Being distributed, the processing elements of the architecture may be organized as subscribers to a global internal network, connected to a server; the basic application software will be broadcast to the distributed processing elements which could, using an Internet / Java like approach, download on request dedicated application software (thus providing flexibility, easier updating and improved local diagnostic).

The aircraft system itself will supplement its mandatory on-board autonomy in being a subscriber to a wider external system, but the expected transmission bandwidth may limit the up and down-loading to data exchange : downloading from outside the application software into the aircraft system according to the mission phases may still prove difficult in term of response time.

5.3 Potential change on the control structure

Control is required to configure statically and / or dynamically the micro-systems.

According to current developments in the domain of Active Array Antenna, careful partitioning of the control structure has to be made for avoiding data transfers bottlenecks. Configuring thousands of sensing elements required an aggregated bandwidth of several Gigabytes / Sec, starting from a less demanding data rate of a few Megabytes / Sec for the high level beam steering control commands (see figure 1).

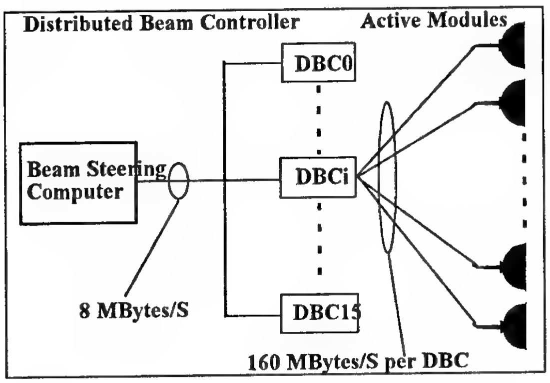

Figure 1 : 1024 modules Active Antenna Beam Control communication bandwidth

Using more "control intelligence" close to the sensing elements would relax bandwidth requirements, at the (modest in term of gate budget) expense of replicating some part of the control processing in each sensing element, the higher level of control processing remaining centralized.

6. ENVIRONMENTAL ISSUES

One of the advantages of spatial integration of avionics (MIA) is that power distribution and cooling arrangement are simpler that in the case of a totally distributed system.

6.1 Cooling

For cooling, distributed systems have the main advantage of reducing the power dissipation volume density but the main disadvantage of requiring the design of a cooling network installed over the complete platform structure.

The latter induces the problem of the cooling fluid. Due to the fact that cooling has to be efficient on circuits installed far away from the fluid cooling system, the choice of a liquid may be required for many circuits in order to use small ducts combined with a powerful pumping system.

Another reason for selecting a liquid as the cooling medium is the size of the Microsystems to be cooled: the smaller the Microsystems are, the higher the heat transfer coefficient has to be. This condition is only valid for a liquid (air has a much smaller heat transfer coefficient and requires then the use of large fins).

Progress is expected from semi-conductors technologies in the field of power dissipation. This is a trend which can be observed, as using finer geometries and lower Vcc helps reduce power consumption for a given number of gates and operating frequency ; but actually semi-conductors companies are cramming more and more transistors on their chips which run at steadily higher frequencies, so that the average power dissipation is steadily higher itself. Some sacrifices regarding the complexity and functionalities of the micro-systems may have to be done to keep the local power dissipation (and thermal signature) within an acceptable range.

6.2 Power supply distribution

For the power supplies, distributed systems require to deliver primary voltages, in the order of 300 Vdc for instance, over the complete platform with local dc/dc converters, in charge of providing the distributed sensors and actuators with the adequate voltages. The use of a lower primary voltage would induce too large currents.

The power distribution could be merged with some medium speed command and control electrical bus, as currently done in the IEEE 1394 bus architecture.

6.3 EMC

The problem of current surges and spikes is part of the electromagnetic compatibility analysis, to be performed at the platform level. Distributed sensors (and actuators) have to send information (data, signals) to a global management system. This information is coming from locations distributed over the complete platform : no interference should modify or pollute this information. This requirement will result in the choice of optical links (photonics technology) for the high speed data network, keeping in mind that the electro-optical devices are very sensitive to EMC.

It must be also reminded that mixing high gain / large bandwidth analog circuits with high frequency clocked digital circuits has never been an easy task; where possible, like in the sensor control structure, the use of static logic (i.e. stopping the clock when appropriate) proved to dramatically reduce the induced noise.

6.4 Maintainability

The connection to the aircraft should be global : electrical, communication and cooling network. The accessibility aspect have not been examined; one expect that local resources of the micro-systems should provide better self-test capabilities (closing the loop by sensing the actuator or actuating the sensor), local redundancy added to the inherent redundancy of a distributed system.

7. ADVANTAGES OF MICRO-TECHNIQUES FOR AVIONICS FUNCTIONS

7.1 Impact on cost

According to the learning curve of products tied to the semi-conductors business, one may expect cost savings from :

- larger quantities produced and co-fabricated electronics,
- complex functionalities achievable and affordable through a large number of interconnected small (and cheap) devices
- embedded self test and diagnostics
- redundancy
- dual use

7.2 Improvement of avionics functions

7.2.1 Vehicle Management System

This domain would exercise both sensing and actuating micro-systems :

- vibration and noise active control,
- active/ passive structural control and fatigue warning for monitoring and on-condition maintenance : engines, gears, moving parts, frames, ...
- fine and better engine control through fluids pressure, flow and temperature sensing and control,
- inertial measurements : mechanical accelerometers, Integrated Optical Gyrometers

Some exploratory studies mention the MEMS usable as :

- active conformable surfaces for advanced aerodynamic control (single flap 1 mm x 1 mm), enabling higher maneuverability and reduced drag,
- local and fine active aerodynamic control through buffeting control, boundary layer control, flux control...,
- active buckling stabilization...

The advent of micro-systems may change so deeply the structure and the safety approach of current VMS that a progressive introduction of these capabilities seems more likely than a radical switch to a totally micro-systems based VMS.

7.2.2 EO / RF Sensors, displays

Some advanced developments have already addressed the issues of distributed elements in the military and industrial domains :

- signal processing (tunable optical filters)
- RF smart sensors (Active Array Antennas)
- EO smart sensors, electronic eye with parallel processing inside the focal plane detector (potential synergy with the industrial / automation / process control fields)
- digital micro-mirror display (10 µm x 10 µm mirrors)

7.2.2.1 Radar

Impact of micro-systems on the radar function can be derived from the current developments in the Active Array Antenna field. A Radar based on MST will use intelligent Transmit / Receive Modules distributed on the aircraft, containing resources for RF, Signal Processing, beam steering and data processing (for partial detection). A central manager will perform the beam control and consolidate the targets partial detection.

7.2.2.2 Electro-optical System

Threat detection and warning from all directions will become feasible using distributed micro-systems.

7.2.2.3 Electronic Warfare Systems

These functions would benefit from micro-systems for :

- aperture sharing with Radar and CNI
- common type of Transmit/ Receive module

- more accurate measure of the DOA
- improved pulse sorting

7.2.2.4 CNI

The current trend is towards integrating the various components of a CNI system into a ICNIA and further merging the RF, SP and DP parts with those of EWS and Radar. The impact of micro-systems may reinforce this trend, or may promote synergy with the commercial telecoms world and limit the commonality with EWS and Radar to using the same type of Transmit/ Receive module sharing the apertures.

8. MICRO-SYSTEMS AND SMART SKINS

Micro-systems may appear as an intermediate step between current equipment and smart skins, but they have more potential synergy with the commercial domains.

9. CONCLUSION

The current effort in standardization and integration for a 2005 time range Operational Capability is to promote domain-level integration (i.e. Common Integrated Digital Processing, Common Integrated RFs,...). The advent of micro-systems and information technology based on networked architecture will favor distribution of the sensors, standardization through scale effect, but may likely push vertical integration across domains to deliver Common Integrated Sensors-Processing - Communication distributed structures for 2020 time range airborne platforms, provided that issues like communication bandwidth and distribution of cooling and power supply all other the platform in an aircraft environment are solved.

Mission Software - The next 25 years

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Summary

The growth in computing technology over the last 25 years has been truly dramatic. The techniques used to develop the software have also seen significant changes.

The growth in avionics software has been no less dramatic. This paper considers the changes that have occurred, and that will continue to take place in the future, in terms of three generations of avionic computing.

The First Generation covers the early application of computing to mission system applications. These mission applications were distributed over few computing centres, with very little communication between them.

The Second Generation of avionics computing is characterised by a major growth in the size and complexity of the software applications.

The changes we can expect over the next generation, the Third Generation, of avionic computing will be as great as those between the first and the second. The most significant change will probably be in the avionic computing architecture, in that Integrated Modular Avionics (IMA) will be at the core of the avionic computing infrastructure.

The need to reduce pilot workload and increase systems performance will demand an increase in the scale and complexity of mission management applications.

To achieve the growth that will be required to support these new applications a significant increase in productivity will be required.

The need to develop highly integrated applications across organisational boundaries will mean an increasing emphasis on integrated teams.

A combination of IMA architecture, with the growth in size and complexity of the mission systems applications, will introduce a number of software management challenges.

Introduction

The growth in computing technology over the last 25 years has been truly dramatic. The impact of this growth is also broadening - no longer is computing the domain of scientists and engineers. The way the personal computer has moved from the office environment to our homes, and the increase in the complexity of the applications that run on them clearly illustrates this. The techniques used to develop the software have also seen significant changes. It was less than 20 years ago that the software developer's environment was one of paper tape, punched cards, teletype terminals and batch mode operations.

The growth in avionics software has been no less dramatic. We can consider the changes that have occurred, and that will continue to take place in the future, in terms of three generations of avionic computing.

The First Generation covers the early application of computing to mission system applications. Examples of such applications are those developed for European aircraft programmes such as the Jaguar and Tornado. These mission applications were distributed over few computing centres, with very little communication between them. The size of these applications was small, in part due to the very primitive tools used to develop them. Assembler programming was still the norm, often targeted at specially developed processors with minimal (and fundamentally limited) memory capacities. Because of the small scale of the computing applications the overall management of the software development process and the products was not yet a major issue, although the need for rigorous configuration control, even for small applications, was often underestimated.

The Second Generation of avionics computing is characterised by a major growth in the size and complexity of the software applications. This is well illustrated by considering the avionics architecture of a present day programme, such as EF2000, where there has been a major increase in the number of computing applications across the avionics system. Many of these applications are very large in their own right, and additionally they are 'loosely coupled' using data buses to form an integrated computing system. The processors used at the core of these computing centres are no longer bespoke designs, but are commercially available and are the same as used in many non-military applications, including home computers. The processing architectures no longer constrain the installed memory size, and high density devices have effectively eliminated this as a fundamental limitation. To accommodate and enable this increase in scale the tools have changed. The use of High Order Language compilers, along with system design tools has resulted in a real increase in developer productivity and end application maintainability. This increase in software size and applications complexity has necessitated more attention being placed on the management of the software development task and the role of the software developer has become a new discipline, not just an extension of the hardware designer's role as was often the case for First Generation avionics computing.

The changes we can expect over the next generation, the Third Generation, of avionic computing will be greater than those between the first and the second. The most significant change will probably be in the avionic computing architecture, in that Integrated Modular Avionics (IMA) will be at the core of the avionic computing infrastructure. The introduction if IMA, when combined with the increasing scale and integration of Mission Software applications will create a number of challenges. The software technology, and the management techniques applied to future developments will need to reflect this.

Computing

Over the previous two generations of mission computing common standards have increasingly been used to improve the quality and interchangeability of equipment. A good example of this is the increasing use of Mil-Std-1553B data buses to provide a common communications infrastructure between equipment. This trend is set to continue because of the current move towards Integrated Modular Avionic (IMA) implementations.

The description of IMA contained here is written from a UK industry perspective, as described more fully in Reference 1.

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 2.

IMA is the implementation of core avionic computing using standard hardware and software building blocks. The hardware building blocks will typically comprise a small number of common systems components, for example, Signal, Data, Graphics and Cryptographic Processing modules. These modules will be interconnected by a very high speed data transmission network. The 'Integration' in the context of IMA covers both the Physical and Functional integration of avionics. Physical integration covers the sharing of common resources, such as racks and power supplies, and Functional integration, the close linkage of functions, such as flight control and power plant control, that in the past have been segregated by equipment boundaries.

Technology Transparency is provided by the adoption of standards which define the external hardware and software interfaces to the IMA modules. The rate of technology development is such that many generations of new technology are produced over the lifetime of a military aircraft. This transparency will provide the potential for incrementally upgrading the avionics with very little impact on external equipment and mission software.

To achieve software technology transparency - the independence of the application software from the underlying hardware - a common operating system is required. This operating system will support a clearly defined application to Operating System interface (APOS).

The OS within the IMA architecture will play a pivotal role, and this will have to be reflected in the integrity level applied to the OS software. The importance of a standard OS is not confined to avionic software, and consequently there are commercial products available which could be considered as candidates for a COTS OS solution. Such solutions would however need to fully address the issues surrounding the development and qualification of a high integrity OS together with the need to achieve very high performance and determinism.

The IMA OS and the underlying hardware modules form a generic platform on top of which project specific application software can execute. Due to the generic nature of this platform it is necessary to provide some means for application specific features of the system to be communicated through to the runtime environment. This can be achieved through the concept of 'blueprints' - application specific objects used to characterize OS performance. Three types of blueprints can be identified:

1. Application blueprints describe the runtime requirements of the application in terms of timing, communications, storage, etc.

2. Resource blueprints describe the capability of the actual hardware resource in terms of processing, communications, storage facilities, etc.

3. System blueprints describe the system/project specific information required to manage the system at runtime. This would include all allowable logical to physical mappings for a given system, covering all functional modes and degradation levels.

The driving customer requirement for future avionics is to be able to achieve an acceptable balance of Life Cycle Costs, Mission Performance and Operational Performance, for any platform, by means of a flexible avionic architecture. IMA has the potential to provide a positive contribution to all three of these drivers in the following way:

LCC - Reduced acquisition and support costs, mainly as a consequence of a reduction in equipment inventory.

Mission Performance - the inherent flexibility of the IMA approach could enable computing assets to be more effectively allocated to mission computing tasks on a phase of flight basis. This will ensure the fuller, and more efficient, use of the available resources.

Operational Performance - mainly covering factors important to the weapon system during in-service use, such as maintainability and availability. To maximise the benefits, the avionic system must have the ability to re-configure itself during operation to 'exclude' faulty modules, and use whatever spare capacity (in the form of spare modules) has been built into the system. Diagnostic and re-configuration software will clearly be required to support this capability.

It can be seen that the level of benefit that will result from the introduction of IMA will vary, depending on the availability of other system management functions. At the basic level, the introduction of common IMA modules will reduce basic procurement and support costs At the other extreme diagnostic and re-configuration/system management software will support dynamic resource management and therefore extended maintenance free operation. It is likely that the full extent of potential IMA functionality will not be available for the initial implementation and the total systems capability will evolve over a period of time.

Applications

In order to maintain a continuous increase in mission performance, the number and complexity of the software applications are increasing. Whilst these functions individually contribute to improved mission performance, a point is reached when these individual functions must begin to be integrated to achieve further improvements. This point can be illustrated by considering the following integration groupings, all candidates for the next generation avionic systems implementation:

Integrated Flight and Propulsion Control - combination of traditional flight control and engine control systems.

Flight Path Management - for integrating a basic navigation capability and providing the integrity bridge for the safe transition of mission planning objectives into commands to the Flight and Propulsion Control system.

Cockpit/Vehicle Management - Conventional cockpit systems integrated with warnings, ground crew and maintenance support functions.

CNI - covering the integration of Communications, Navigation and Identification functions.

Integrated Sensors - the combination of traditionally discrete sensor functions to provide optimum performance. An example of this would be the coordination of EO and RADAR operation

to produce high quality, accurate target data with infrequent RADAR emissions.

It can be seen from this summary that systems integration will not just be confined to these discrete 'integration groups' and there is in fact a strong functional relationship between a number of them. This is further illustrated in figure 1.

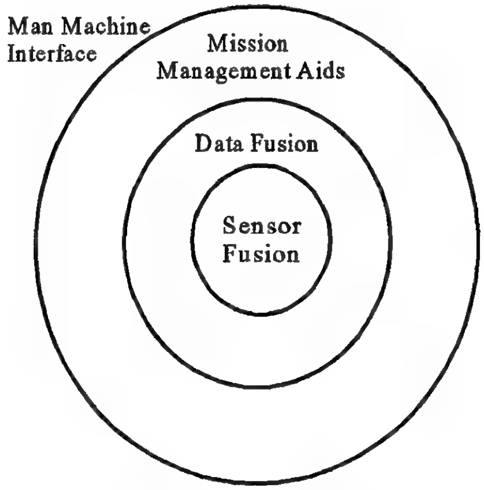

Figure 1. Example of Software Integration

In this illustration, the provision of coordinated data from multiple sensors is covered by the Sensor Fusion function. The processing of data from multiple sensors to provide complete situational awareness is covered by the Data Fusion activity. The pilot workload could then be further reduced by the provision of a Mission Management Aid (MMA), which would combine this enhanced situation awareness with knowledge of the mission plan to provide advice to the pilot.

It is clear from this description that a system of this type would involve the development of a large quantity of high complex, and highly integrated operational software. The key difference between Second and Third Generation avionic systems is not just the growth in size, but is also in the integration between them. A general consequence of this trend towards increasing integration is that the software development task becomes more complex. One advantage of a second generation mission system is that the software functions are relatively discrete, and are embedded within separate equipments. This will no longer be the case in Third Generation avionic systems, and the software partitioning and packaging needed to manage the complexity of the software development task will have to be achieved in another way.

Software Technology

Tools

As the scale and complexity of the mission software increases, so does the dependence on tools to support the development process. For third generation mission systems the range of tools required will be such that the management of the tools will in itself be a major issue. To illustrate this point, a typical tool set will cover the following functions:

Requirements Capture
Requirements Analysis
Software Design
Compilation
Static Analysis
Test Case Generation
Configuration Management
Traceability Management
Documentation Processing

In previous generations it was common place for software development organisations to develop bespoke tools, specifically configured to address the needs of the Aerospace industry. The trend is now towards the use of commercial products wherever possible. This frees avionic systems developers to concentrate on their core business of developing avionic systems. There is however a loss of control in terms of the management of support, and future tool developments, which has to be recognised.

It is clear that a complete systems development tool set is required, and from a tool management and integration viewpoint it would seem attractive to consider the procurement of a complete solution from a single vendor. In practice it is very unlikely that any single tool vendor will ever be able to provide an adequate complete tool set. Instead a range of tools will be procured from a range of 'best in class' tool suppliers. However, the procurement of a number of different tools from a range of tool vendors will mean that the task of tool-set management will become more complex. Tool set changes, to fix bugs and introduce key enhancements, are inevitable and this will require careful control to avoid configuration management problems.

The use of an IMA architecture will have an impact in this area. IMA provides the increased potential for software applications to be developed by multiple organisations for integration onto a common computing system. In previous generations, this was generally not the case, and the physical boundaries between avionic equipments meant that the use of a common tool set was not a technical necessity. For an IMA architecture it is clear that either a common tool set is required, or tool interface standards are defined which provide for the interchangeability of tools. In reality, the confidence that is gained from the use of a common tool set is always going to be greater than the standards based alternative.

There is now some experience within the industry of software tool set management, both on the EF2000, and more recently on the F22 programme. This experience will be invaluable in steering the approach adopted on future programmes.

Ada

Ada was originally developed with the intention of addressing

the proliferation of computing languages, and the associated support problems, on US military programmes. In achieving these objectives the language has been broadly successful. The rigorous adoption of a language standard has certainly provided for the interchangeability and reuse of software in a way that is not possible for other widely used languages, such as 'C'. It would also be reasonable to say that there is no better language to support the development of high integrity software.

The use of Ada in the commercial marketplace has been very limited, and therefore there is growing pressure to allow more flexibility in the adoption of Ada. A recent report produced by the US National Research Council (NRC) at the National Academy of Science, has produced the following recommendations:

1. "Continue to require Ada for its warfighting software, and drop the Ada requirement for its other software."

2. "Provide roughly $15 million per year for infrastructure support, or drop the requirement to use Ada entirely."

3. "Make programming language decisions in the context of a Software Engineering Plan Review process."

Clearly these recommendations, if adopted, provide more flexibility and support the concept of "intelligent choice". The negative consequence of this policy would however be a reducing marketplace for Ada support tools, and the point may occur where the market critical mass is reached and an increasing number of tool vendors discontinue their support of the language.

It would overall seem likely, especially when considering the suitability of the language for high integrity mission applications, that Ada will be used for the next few years. The long term future of the language must however be open to question.

Rapid Application Development/Code Generation

In this context the term Rapid Application Development (RAD) will be used to describe the automatic generation of code from a systems analysis specification or model. The tools that support this concept are providing the potential to achieve the major increases in productivity required to counterbalance the predicted growth in the software content of mission systems. Tools to support the automatic generation of code for specific 'niche' application areas have been available for some time, but more generalised tools, typically based on a formalised use of Object Oriented Analysis (OOA) techniques are now becoming available. These tools provide the potential for the much broader use of code generation, for instance, across mission systems applications.

For mission software the software verification is a major cost element. The use of RAD technology will only benefit in this area if a sufficient level of verification is applied to the tool itself, thereby reducing the level of verification required on the code produced by the tool. For instance RTCA/DO-178B (Reference 2.) states that "the objective of the tool qualification process is to ensure that the tool provides confidence at least equivalent to the process(es) eliminated". This fact will have to be recognised by the tool developers and the potential users and an appropriate business model developed to support the work required.

Another potential way of reducing the tool qualification overhead is to claim credit for service history, and the most effective way of achieving this could be for the tool vendors to accumulate this history from the complete user base, for the benefit of all users. This process would need to recognise the importance of rigorous management of tool updates to minimise the necessity for tool (and Mission Software) re-qualification

Software Management Issues

Successful avionic software development is not only dependent on the availability of the right software and computing technology. This technology must be accommodated within a management framework encompassing the organisational, process and commercial elements that are all necessary to achieve a successful programme.

This section provides an overview of some of the general software management issues relevant to future programmes.

Productivity

The volume of software increases dramatically between successive generations of avionics systems. UK industry estimates suggest that the software required for the next major programme could be approximately three times bigger than that developed for EF2000. Software development productivity will of course need to increase to at least keep pace with this growth - even if there are enough engineers at the right skill level to take on the task, the costs would be too high and the management task too difficult.

The reduction in productivity with increasing team size is well documented and is supported by much empirical evidence. Faced with a software development task of great complexity, to be undertaken within very tight timescales, most informed managers would attempt to assemble a small team of the most capable people.

The necessary increase in productivity must therefore by achieved by other means. Reuse has been sold as one way of achieving this. Reuse is already applied to avionic applications, but it is often informally controlled, involving the evolution of existing documents and data into new products. Institutional reuse, involving the use of formally controlled software component repositories, has not been applied to a major degree for avionics mission software. One reason for this must be the constantly evolving nature of this software and the therefore limited scope for inter-project reuse without modification. To benefit from the investment required to set up and sustain the repository, and the increased overhead in developing reusable components, then a degree of stability must exist in the application domain, and this is not the case for mission systems applications. With the increased use of standardised computing elements, such as in the case of IMA, then the scope for intra-project reuse - reuse within a single programme - could produce real benefits. However, before the project-based infrastructure is put in place a full payback analysis should be carried out to justify the up-front investment.

Another approach to the productivity problem is to employ Rapid Application Development (RAD) techniques, as described previously. RAD in this context applies to the use of simulation and prototyping tools linked to software code generators. The application of these tools to the total mission systems application domain is still some way off, but the potential for a major improvement in productivity has been demonstrated, and it is likely that it will be by the pursuit of this technology, already being applied in industries with less demanding integrity and performance requirements, that the necessary productivity improvements will be achieved.

Organisational

The increasing integration of software applications in an IMA computing environment will have a major impact on development organisations. Closer working relationships between parties is important and Integrated Product Teams are likely to become the norm in the future. The functional boundaries that exist with a federated computing architecture do at least provide clear lines of responsibility and closer working relationships will be necessary if wasteful disputes are to be avoided. Truly Integrated Product Teams require Information Technology support to realise the potential for a virtual office environment, where physically dispersed teams can cooperate as if no boundaries exist. Many organisations are implementing new Information Systems initiatives, but few of these are taking into account the need to integrate organisations. In the same way, internal Business Process Re-engineering initiatives should be integrated to provide process improvement not just within organisations, but up and down the supply chain.

System Certification

An approach to systems certification has been developed during First and Second Generation avionic systems developments. This process benefits from the loose coupling between federated avionic subsystems. For a system built around an IMA architecture the hard boundaries that have existed between equipments will not exist, and therefore a modification to this approach to certification will need to be established. This modification will also need to take into account the increasing functional integration between applications and a system design that is highly reconfigurable, all of which adds to certification complexity.

A high integrity OS must contribute to this process by providing a "firewall" between applications.

Documentation

The production of good quality documentation is a key part of the software development process, and effective support would be impossible without it. However, the volume of documentation presently required to support avionic software development is extreme. Significant productivity improvements are possible if the documentation can be produced as a direct by-product of the development process instead of being an end in itself. In extreme cases deliverable software documentation can be used to trigger milestone payments and in such cases the emphasis of the development effort can switch to the documentation rather than the working product.

The switch to process management standards, such as the Software Engineering Institutes Capability Maturity Model, and the new international Software Process Improvement Capability dEtermination (SPICE) frameworks are key. Amongst other benefits they are reinforcing this trend away from rigid process standards, so that organisations can be free to optimise their internal operations, whilst still achieving the key objectives.

Human Resources

As more and more industries utilise computing technology, the demand for programming staff increases. The use of RAD techniques has already been discussed as a way of improving productivity, and it is also likely that this will not just impact the number of people required to undertake Mission Software development, but also the type of skills required. The use of automated code generation techniques will mean that the specification of the system will be the major task and therefore avionic systems design skills are likely to dominate. Software development skills will still be required, but these will be focused on the aspects of system design such as OS development, and hardware to software mapping. The skill level of the remaining software engineers is likely to increase due to more specialised nature of the development tasks.

These staff issues are likely to be very similar across all industries requiring high performance, real time embedded systems. The automotive and mobile communications industries are two key examples where there will be increasing competition for these key programming skills.

Conclusions

Avionic systems have become increasingly dependent on software to provide mission systems functionality. This trend will continue in the future and the appropriate conditions must be put in place to ensure that the software can be developed cost effectively. The avionic industry will become increasingly dependent on the cross over of technology from the commercial marketplace, and this will require cultural change in the Aerospace industry. Also, to achieve the full potential of the IMA concept, a number of changes will be necessary to traditional development processes.

References

1 Parr, G.R. and Edwards, R.A, Key Issues in Integrated Modular Avionics - IAWG Viewpoint, The Royal Aeronautical Society conference on Integrated Avionics, 12th October 1995.

2. Software Considerations in Airborne Systems and Equipment Certification, RTCA/DO-178B.

DISCUSSOR'S NAME: R. Lachenmaier

COMMENT:

For harnessing multiple computers the NUMA (Non Uniform Memory Access) method is generally used by the commercial world. We at SF have explored this area and have been generally pleased with the results. Can you comment on any experience you might have had using this technology.

AUTHOR/PRESENTER'S REPLY:

We have not looked at this particular method. It would appear to be very attractive from a pure performance viewpoint, but it may be that the ability of such an architecture to provide deterministic operation would need to be further considered.

DISCUSSOR'S NAME: R. Lachenmaier

Have you looked at establishing an open architecture at the software application level? This would be useful for plug and play third party software.

AUTHOR/PRESENTER'S REPLY:

An open system at the software application level is a design goal to support the integration of applications from different avionics suppliers. Once this has been realised, then the integration of software from any source should not be a problem, providing the integrity requirements have been met.

DISCUSSOR'S NAME: H. Davies

QUESTION:

Will there ever be a commercial market for a high level language and tools of adequate integrity to meet the needs of military life-critical systems?

AUTHOR/PRESENTER'S REPLY:

There may not be an adequate market for life critical-systems. However, there may be a requirement for high integrity tools to support a broader range of applications, including those that are financially critical and high reliability communications software.

ADVANCES IN FULL MISSION ENVIRONMENT SIMULATION TECHNOLOGY

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SUMMARY

The significant advances in the field of simulation technology allow a more and more realistic reproduction of a weapon system's tactical environment. On the other hand, modern weapon systems place increasingly high demands on the quality and complexity of training equipment. In particular, such weapon system can no longer be regarded as autonomous, individual components. Rather, they have become an element of a complex military structure fulfilling operation-specific tasks. This leads to the conclusion that the design of training equipment should not only be system-specific but also operations-specific. The technologies which have been developed over the last years, especially in the fields of tactical simulation, computer-generated forces (CGFs) and networking, now enable the flexibility which is mandatory for structuring such a training system. The technological basis required for creating such a system will be discussed in this paper on the example of a Complex Air-Warfare Demonstrator, which has been developed under a European study contract.

1 INTRODUCTION

Military operations embody tightly coupled and complex interactions. Operations, especially offensive counter air, air interdiction and the support of ground forces through interdiction or direct fire - or equivalent Army and Navy combat actions - require the joint effort of a comprehensive mixed force, the human involvement in distinguished mission executions and the use of defined and proven command and control procedures. In this respect, the complexity of modern weapon system places ever higher demands on quality of the operating crews' training. More particularly, those training issues focusing on the mission as part of complex military operations necessitate a highly realistic integration of the respective system into its „natural" tactical environment. Highly sophisticated simulation technology is increasingly used in order to obtain the best possible efficiency with regard to training quality, and to achieve the necessary flexibility in reproducing the mission environment.

2 TRAINING SYSTEMS

The definition of a training system for a specific weapon system, where crew training should be mission-specific, i.e. embedded into the "natural tactical environment", can be approached according to two viewpoints:

1) System structures are defined strictly in accordance with the respective requirements of a specific weapon system. This concept is the traditional approach for designing so-called Full Mission Training simulators. As a rule, they are designed as local training system which reproduces the weapon system's entire tactical environment by means of (CGFs). In some cases, instructors are also included. More recent systems, for example, provide the possibility to place CGFs under manual control of the instructor during the simulation.

2) A training system is however not only laid out in accordance with the requirements stipulated by a single weapon system, but rather on the basis of complex military operations. This rather new concept mostly leads to a distributed simulation, where all players in the underlying military operations can be represented as CGFs. In addition, such a system then allows to incorporate "manned" simulators specific to an exercise, or to replace the CGFs by the former in a specific scenario. The advantage offered by a training system structured in this way is its enormous flexibility. For instance, training the crew of a weapon system can be carried out throughout several levels, where the top level is a complete embedding of the crew as part of a "team" within a complex military operation.

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Moreover, the orientation of the reproduction of tactical environment in view of the type of one or several military operations no longer limits the system to crew training on a given weapon system, but allows the embedding - and thus the training - of all weapon systems joining in an operation in the form of "manned" simulators. This concept also calls for incorporation of real C3I systems, which provides highly interesting options with regard to mission rehearsal of complex military operations.

3 DESIGNING TRAINING SYSTEMS IN VIEW OF OPERATIONAL REQUIREMENTS

Under the European EUCLID RTP 11.3 study, a consortium of 6 companies and institutes from 6 different countries led by CAE Elektronik GmbH, defined a Complex Air Warfare Training system including all the forces participating in an air-combat scenario.

In order to achieve the best-possible progress of the activities, four main work packages were defined and allocated to the responsibility of the different consortium members.

WP 1: Mission Rehearsal Capability.
WP 2: AI Tools
WP 3: Mixed Forces & Networking
WP 4: C3I System Integration

An analysis of training requirements elaborated together with military experts from all participating nations formed the basis for building, through several stages, a Complex Air Warfare Demonstrators throughout 1996 and 1997. The

These demonstrators encompassed:

- 2 full-mission simulators
  - MRCA Tornado
  - F16
- 4 generic cockpit stations
- C3I simulator
  - Fighter Allocator (1 manned)
  - Intercept Controllers (2 manned, 6 computer-generated)
- Enhanced Interactive Tactical Environment Management System (ITEMS)
  - up to 100 computer-generated scenario elements
- Artificial Intelligence Target Station
- Exercise Controller Station

On the basis of this example, we will discuss, in the following, the relevant techniques for an operation-specific training system.

4 WHY USE COMPUTER-GENERATED FORCES?

A number of reasons advocate the use of CGFs for representing scenario elements in a complex air-warfare simulator. It would be very difficult, to include all - and particularly enemy - forces within such a complex system exclusively by integrating manned simulators. On the one hand, there would nowadays hardly be sufficient systems - both in terms of quantity and simulation quality - available to provide all the required types of scenario elements, and on the other hand, the logistic expense for operating such a system would soon defy its practical utility for training.

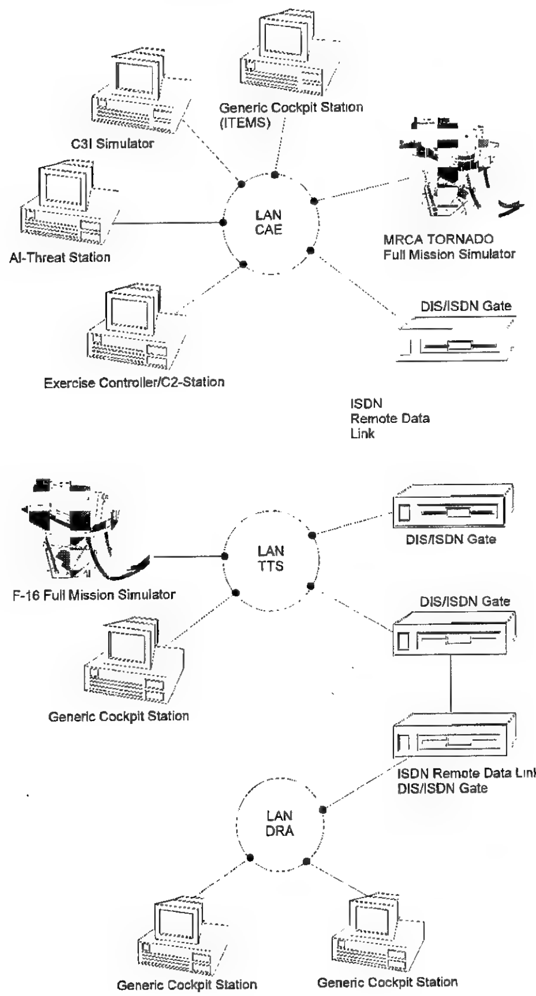

Fig. 1: Structure of complex air warfare demonstrator

In addition, there are other aspects which make the inclusion of CGFs into a complex air-warfare simulator seem sensible. As is true for any device used in aircrew training, it must be possible, in such a simulator, to accurately set up the simulated tactical environment of the human participants in accordance with the desired training program. Furthermore, the course of the simulation should be completely reproducible, allowing to repeat an exercise as a whole or in part following its analysis. These requirements can be fulfilled much more easily when using CGFs, as there is no human component which would be hard to assess in complex scenarios.

5 REQUIREMENTS PLACED ON CGF AS PART OF A COMPLEX AIR-WARFARE SIMULATOR

To put it in simple words, the same requirements apply to CGF as they would be valid for a manned simulator in the same situation. In this respect, a restriction is admissible only for those scenarios which are based solely on interactions between CGF which cannot be acquired by the sensors of a scenario element represented by a manned simulator. In this case, it would be sufficient to correctly represent the result of such an interaction, instead of the interaction itself. Even if such a measure might, on first sight, look like a restriction of the simulation quality, its application, i.e. the anticipation of simulation courses, is one of the few possibilities, in such complex systems, to bring the human players within the scenario into an exactly predefined situation at a given time. However, the requirements placed on CGF's simulation quality with respect to the realistic reproduction of interactions with human players within the scenario are particularly high. The same applies to interactions between CGF themselves, in as far as these interactions occur within the range of the sensors of a manned simulator.

The development of the demonstrators used under EUCLID RTP 11.3 laid special emphasis on the faithful reproduction of interactions between manned and computer-generated scenario elements:

- Utilization of realistic motion-sequence models with parameters adapted to the respective element, in order to achieve the most accurate representation of motion in the manned simulators' out-of-cockpit view.
- Determination of realistic reflection characteristics for target acquisition by the sensors of a manned simulator (radar, IRST, laser etc.) or the seeker head of a guided missile
- Presentation of the tactical environment of a computer-generated scenario element through the simulation of its passive and active sensors.
- Determination of the virtual crew's visual range, allowing for weather conditions and motion parameters.
- Simulation of active sensors such as radar (navigation, search and track) and laser (range finder and designator).
- Simulation of passive sensors such as warning receivers (radar, laser, etc.).
- Simulation of information exchange between CGF, taking into account elementary filter functions.
- Simulation of countermeasures for expedient jamming of sensors of other simulators (simulators also as guided missiles).
  - RF jammer
  - IR jammer
  - radio jammer
  - chaff (decoy and corridor)
  - flare
- Simulation of weapon deployment by CGF, with flight paths determination for:
  - rockets, taking into account the firing conditions, burning duration, thrust etc.,
  - ballistic weapons, taking into consideration the firing/dropping conditions and their ballistic parameters,
  - guided missiles, allowing for missile parameters and guidance information provided by the simulation of the missile's seeker head.

This simulation includes the weapon-specific stimulation of the corresponding sensors of a manned simulator (e.g. out-of-cockpit view, RWR etc.).

The simulation of voice-based interactions between manned simulators and computer-generated scenario elements has proven to be a big problem. Particularly, the algorithms available for voice-recognition do not meet the high demands on recognition accuracy needed for the analysis of voice transmissions. In many a case, erroneous interpretations of voice information by the computer simulation would have led to unrealistic scenario developments, so that the demonstrators developed under EUCLID RTP 11.3 relinquished such features. Algorithms which will be available in the near future, and which will allow very accurate

voice recognition, make the use of CGFs in the tactical environment of manned simulators seem all the more profitable.

6 CGF WITHIN THE NETWORK

With respect to the use of CGF in distributed complex simulations such as the air-warfare simulators developed under EUCLID RTP 11.3, a key consideration is how to provide for their most sensible implementation within such a network.

In accordance with the DIS protocol's underlying philosophy, the 'owner' of an element acting within a DIS network is the sole responsible for its simulation. This not only includes the basic simulation parts such as simulation of the flight path of a computer-generated interceptor, determination of interactions between own sensors and those of other elements acting in the network, flight path computation of guided missiles fired by the ownship, determination of degraded ownship functionalities after taking hits, but also the more abstract features of the simulation of an element, such as for example the realistic reproduction of situation-dependent behavior.

However, if this philosophy is observed without any compromise for defining the structures of a greater network, this will obviously result in a multiplication of the simulation models existing within the network, leading in turn to an unnecessary increase in hardware and software requirements. Problems will ensue in particular where the requested simulation models do not exist at all, or without the desired quality. Moreover, it must be taken into account that both CGF and manned simulators may be controlled by a higher level of command. By way of example, a computer-generated interceptor may, during a scenario, be allocated to an intercept controller who may be realized on a different computer.

In order to achieve the highest possible flexibility, the concept of the air-warfare demonstrators developed under EUCLID RTP 11.3 was designed with an approach that made optimum use of the resources available for their realization, but which will also increase the network's load accordingly, depending on the latter's structures. The simulation of certain, computer-generated scenario elements was distributed onto several simulators depending on the situation. Status information and control instructions for these elements were exchanged between these simulators by means of the application-specific part of the signal PDU. This solution allowed us, for example, to dynamically place the CGF under the control of different simulators during a scenario run, enabling the simulators to have an influence on the CGF's tactical behavior. This means that a C3I simulator whose task was, among others, to control the computer-generated interceptors, needed neither the flight models nor models for the simulation of their radar systems and other sensors, or their interactions with sensors of other active scenario elements, in order to provide a realistic simulation of these interceptors.

The required simulation models were executed centrally on a single computer which, on the basis of rules created and assigned to the CGF during the scenario generation, was able to determine a situation-consistent tactical behavior for those CGF which were not controlled by an external simulator.

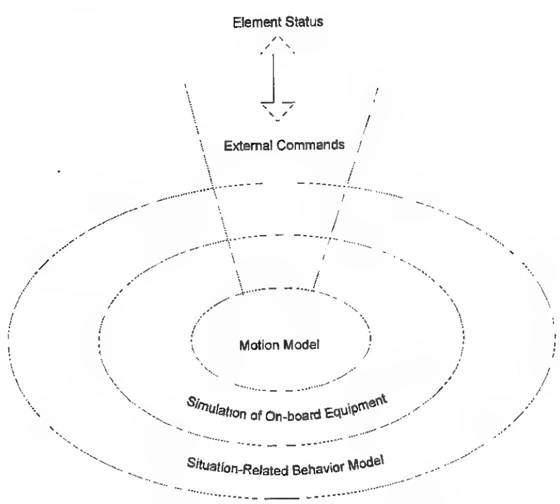

Fig. 2: Simulation model for CGF in distributed simulations

In this way, the transmission of a simple command could trigger an air combat, in-flight refueling, flying of a combat air patrol (CAP), or initiate a landing procedure. Moreover, the C3I simulator was able to define the flight route of an element under its control by specifying the desired speed, altitude and heading.

The undeniable inconvenience of this solution is that a range of the status information which is absolutely indispensable for the C3I simulator to make decisions about the control of an element generated and administrated in the ITEMS simulator needs to be transferred via the DIS network.

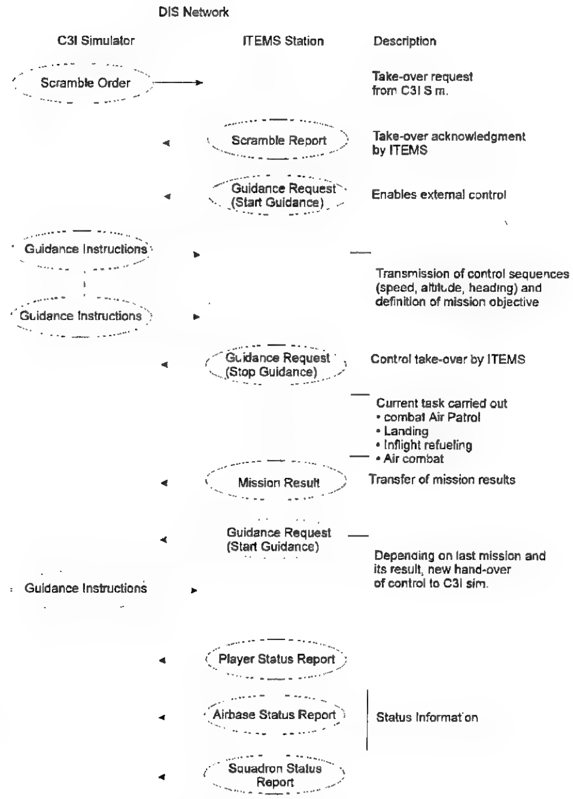

Fig. 3: Communications between ITEMS and C3I simulator

However, given the limited number of scenario elements (some 80) for the EUCLID RTP 11.3 demonstrators, this did not significantly interfere with the network load, thus not compromising the advantages mentioned above.

The only conceivable alternative was to group the simulations of all higher command levels and of their related scenario elements on one computer each of the network, so that only the scenario elements themselves would have to be reproduced on the DIS network. However, such a solution can be recommended with restrictions only.

On the one hand, the connections between higher and lower command levels would be statically predefined due to the structure of such a simulator complex, severely impeding its flexibility with respect to possible air-warfare scenarios, and on the other hand it will entail an inefficient use of available resources, because it may be necessary to implement the same algorithms for generating and managing CGF on numerous, different computers.

7 ARTIFICIAL-INTELLIGENCE-CONTROLLED COMPUTER-GENERATED FORCES

Another is the use of methods and algorithms stemming from the field of Artificial Intelligence. Especially for the controlling of CGFs, this technique provides astounding possibilities. For example, a situation-dependent behavioral pattern can be realized through a knowledge-based system. For the CGFs created under the EUCLID RTP 11.3 study, each element was assigned a so-called doctrine during scenario creation. From the behavioral rules contained in these doctrines, a realistic, situation-dependent behavior was derived while taking into account the "knowledge" about the respective element's tactical environment gained through the simulation of its on-board equipment.

The doctrines were structured similarly to a computer program written in a conventional programming language. For example, several rules (statements) were grouped into so-called rule sets (subroutines) which significantly contributed to a clear structuring of doctrines. Figure 4 depicts the principle structure of a close-combat doctrine on the rule-set level, as it was created for computer-generated interceptors. Figure 5 shows a simple example for a single rule.

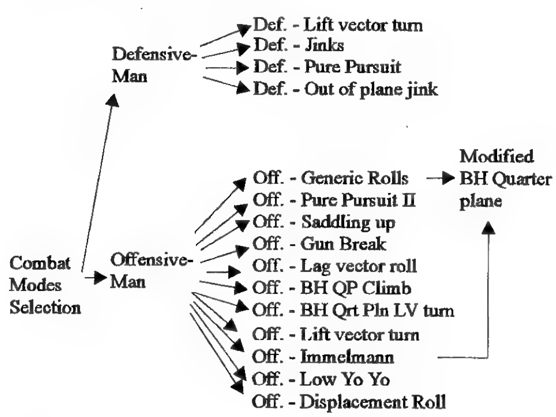

Figure 4: Example of a close-combat doctrine for an F/W on a ruleset basis

IF	RWR detecting track signal	= TRUE
and	CM / ECM turned on	= FALSE
THEN	Execute Response	Turn radar jammer ON
	Execute Response	Fire chaff

Figure 5: Example of an individual rule

It was also investigated to what extent the implementation of a learning capability makes sense for CGFs. Although the final evaluation of the study results has not be fully completed, the employment of learning algorithms during the runtime of an

exercise does not seem commendable. What was absolutely helpful, however, was the subsequent evaluation of the courses of simulations with regard to optimizing a doctrine.

8 SCENARIO GENERATION AND MANAGEMENT

The operation-oriented structure of a training system places high-requirements on the generation and management of scenarios. The concept chosen for the Complex Air Warfare Demonstrator included a Scenario Management System for this purpose which managed all components of a scenario in a thought-through hierarchy in the form of databases. To achieve the best-possible flexibility, the runtime software only provided functional models, instead of finished elements. These were then conditioned for the exact functionality of the element by specifying element-specific parameters by means of an editor system, and then saved as part of the associated database. This concept allowed to build libraries pertaining to all relevant scenario elements, which significantly accelerated and simplified the creation of new scenarios. Fig. 7 outlines the architecture of the Scenario Management System used for the EUCLID RTP 11.3 study.

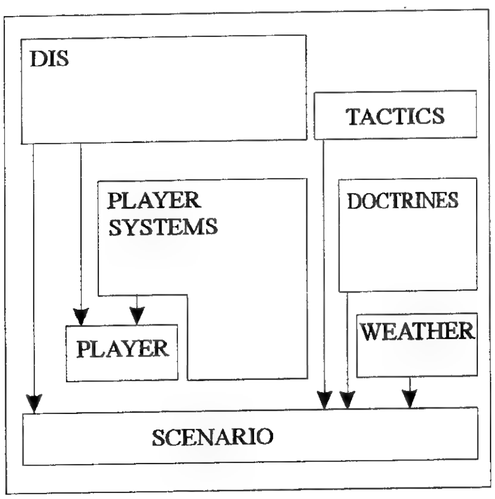

Figure 6: Scenario database architecture

9 INITIALIZATION OF DISTRIBUTED SIMULATIONS

If the simulation of CGF is performed as described above, i.e. distributed onto several computers, this places certain requirements on the initialization of such a system. In particular the apportioning of behavior determination to several, decentralized command levels suggests that the system initialization should be divided into several phases. The approach selected for the EUCLID RTP 11.3 demonstrators allows for the fact that, for initialization, a higher command level may require information from lower command levels which may not even yet exist at the time of initialization. For this purpose, system initialization was divided into two phases, local and global. A separate station acting as Exercise Controller performed the initiation and control of the initialization, and later the control and monitoring of the entire system during a running scenario. The first phase was the local initialization of the simulators within the network, e.g. selection of a weapons configuration for a manned full-mission simulator and determination of its initial coordinates. After the local initializations of all simulators were accomplished successfully and confirmed to the Exercise Controllers, the latter initiated the second phase. In this phase, the local status of every scenario element was represented on the DIS network, which was then used for further initialization by the stations which were, for example, responsible for simulating the higher command levels.

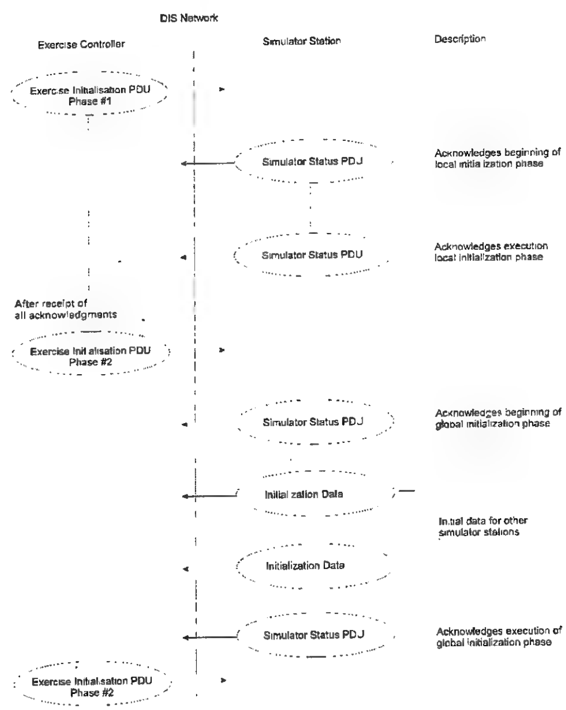

Fig. 7: Initialization of distributed simulations

This phase encompassed e.g. the initialization of the C3I simulator with information regarding the allocation to squadrons, the state of readiness of the interceptors available in the scenario, and their

initial positions (flying on CAP, or located on airbase). Once the Exercise Controller had received all acknowledgments for the completion of the global initialization, it performed the coordinated start of the scenario run.

10 NEW TECHNOLOGIES FOR BUILDING DISTRIBUTED SIMULATIONS

At this time, the most advanced standard for building a distributed simulation is certainly the HIGH-LEVEL ARCHITECTURE which in turn is part of a COMMON TECHNICAL FRAMEWORK (CTF) designed under responsibility of the Defense Modeling and Simulation Office (DMSO). The objective in defining this CTF was to facilitate the interoperability of all types of models and simulations among themselves and with C4I systems, as well as to simplify the reuse of M&S components. Fig. 8 shows a functional overview of HLA.

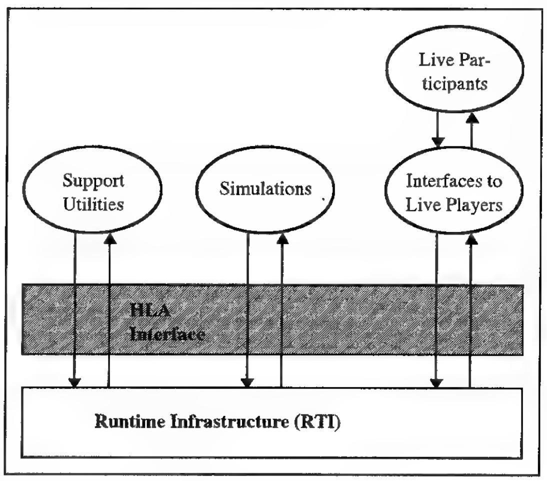

Fig. 8: Functional overview of HLA

The formal definition of HLA was done by specifying the following parts:

- HLA Rules
  A set of rules which must be followed to achieve proper interaction of federates during a federation execution. These describe the responsibility of federates and of the Runtime Infrastructure in HLA federations.
- HLA Interface Specification
  Definition of the interface services between the Runtime Infrastructure and the federates subject to the HLA.
- Object Model Template
  The prescribed common method for recording the information contained in the required HLA Object Model for federation.

The central functional element of HLA is the so-called Runtime Infrastructure (RTI). The RTI can be considered as a distributed real-time operating system, which assumes the following tasks within a federation:

- Federation Management
  Create and delete federation executions
  Join and resign federation executions
  Control checkpoint, pause, resume, restart
- Object Management
  Create and delete object instances
  Control attribute and interaction publication
  Create and delete object reflections
- Time Management
  Coordinate the advance of logical time and its relationship to real time
- Declaration Management
  Establish intent to publish and subscribe the object attributes and interactions
- Ownership Management
  Transfer Ownership of objects/attributes
- Data Distribution Management
  Supports efficient routing of data

Detailed information on the HLA can also be found on the Worldwide Web:
http://www.dmso.mil

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He has been in CAE Elektronik Gmbh's Software Engineering department since 1987, focusing on full mission training simulators for the German Air Force.
Since 1994, he has also been concerned with implementing the EUCLID RTP 11.3 study dealing with the designing and development of a Complex Air-Warfare Training System.
In 1997, he became a group leader in the company's Software Engineering department.

Virtual Environments: Visualization Throughout the Combat Mission.

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Summary: All levels of the military command structure, from senior military commanders to the forward combatant require visualization of data and fusion of tactical and strategic information. Specifically, visually oriented displays provide intuitive, readily understandable information that can be easily interpreted and acted upon. Visual systems provide a variety of data and information including maps, terrain elevation, imagery, iconics, symbology, and text. The effective use of military information in a combat situation should be specific to the individual mission, yet be consistent with all other levels of the military command structure. Consistency among and between command levels is critical to support coordinated planning, execution, and after-action activities.

This manuscript and associated presentation provide a discussion of the application of virtual visualization environments within a hierarchical requirements structure, based on warfighting functional requirements. Additionally, this presentation relates functional requirements to system characteristics and discusses utility of the information to airborne applications.

Introduction: The ability to convey information is an age old issue. Plato discussed the mental process of such conveyance in terms of understanding, reasoning, opinion, and imagination. Plato reasoned that the ability to impart complete or "pure" information provided the highest levels of comprehension.[1] In the present, as well as the past, the ability to convey complete information is critical to human endeavor whether in peace or war. Visualization enhances the conveyance of complete information.

Visualization of military information presents unique challenges and perplexing technological trade-offs. Achieving the right "look" or "feel" for combat data is difficult. Further, the visual rendering of military information is the product of a particular system design and its inherent cost considerations. A complicating factor is the gap in communication/interpretation between users and developers. Senior decision makers, of the slide rule generation, are often determining system needs for operators who grew up with video games and personal computers.

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 2.

Discussion: Visualization requirements have driven today's visualization capabilities which span from simple line depiction to the fusion of multiple sources of data and rendering of high fidelity, geo-specific perspective scenes in real-time. This range of capabilities has been employed to support mission planning, rehearsal, execution, and debrief; intelligence efforts; and modeling and simulation efforts.

The US Defense Science and Technology Guidance for Joint DoD applications lists several areas affecting visualization capability enhancements. Specifically, 1) Command, Control, Communications, and Computers (C^4): provide common, accurate, mission-tailored pictures to all warfighters, and develop the ability to "learn" from users, to improve visualization; 2) Intelligence, Surveillance, Reconnaissance (ISR): improve situational awareness, manage information and aid decisions; 3) Manpower/Personnel: determine optimum human/computer tasking, improve decision-making, reduce user workload, and reduce crew/manning requirements. These capability enhancements will foster performance improvements and manpower reduction by improving warfighter performance, and reducing workload by tailoring displays to user requirements.

Common and concurrent visualization capabilities throughout and among the command levels are critical. Examples of advanced applications for simultaneous visualization at multiple levels include recent activities for Bosnian operations, planning and rehearsal during Deliberate Force operations, use of virtual environments for the Bosnian peace talks in Dayton, Ohio, exploitation of the Joint Strike Fighter (JSF) development program, investigation of US Secretary of Commerce Brown's crash, and conveyance of imagery data to the US National Command Authorities. Virtual environments offer the opportunity to "see into the future" and allow operators to extend their understanding of the present situation and better prepare for future events through enhanced situational awareness. These virtual environments also provide the user with augmented realism. This is done by incorporating actual situations with the virtual environment giving the operator an expanded understanding of the environment. An example in an airborne application would be the use of a 3D visual representation using geolocated imagery and digital terrain data to provide a virtual Visual Flight Rule view during poor weather conditions to enable the pilot to "see" through the weather.

The US Navy program called The Tactical Moving Map Capability (TAMMC), has stated requirements and is now developing capabilities to display 2D moving map. TAMMC is planned for F-18, AV-8B, and AH-1W with potential applications to the V-22, UH-1N, F-14, P-3C, and H-60. The 2D moving map requirements for TAMMC are included in Table 1. Figure 1 provides a snapshot of a 2-D rendering capability of the current TAMMC program.

Planned TAMMC improvements include implementation of three dimensional functions. These 3D perspective scene generation needs were assessed in terms of user suggested enhancements to Bosnian prototype systems and desired JSF capabilities. The 3D perspective visualization requirements for future TAMMC capabilities (Table 3) are being developed by a number of sources including the Joint Strike Fighter (JSF) program and can be found in Table 2.

Many of the 3-D scene perspective requirements are based on situational awareness needs related to the JSF Strategy To Task framework. During the requirements definition process, users have asked that future visualization systems incorporate various sensor imagery, provide simulations of sensor and performance predictions, extrude cultural objects, provide aircraft appropriate flight dynamics, add weapon simulations, display threats dynamically and accurately, provide interface to mission planning systems, and permit the user to retrieve coordinates from simulated scenes. Figure 2 provides a notional view of a 3D perspective scene capability using photo-based imagery, elevation data and appropriate tactical strike symbology. The scene contains threat domes, target locations, collateral damage warning, approach restrictions, sensor updates and weapons effects.

Table 1. 2-D Requirements Based on the US Navy Tactical Air Moving Map Capability.[2]

Change of Map scales and features in real-time	Mag/Zoom from 1 to 1 up
Coverage area in standard scales (ex. 1 inch to 5 million meters)	Programmable Color palettes
Variable Map Scales between 2.5 and 250 nm	Standard Symbol Generation
Map orientation north-up or heading-up	Dynamic overlays
Center/de-center	Dataframe rates
Sun/moon shading	Slewing

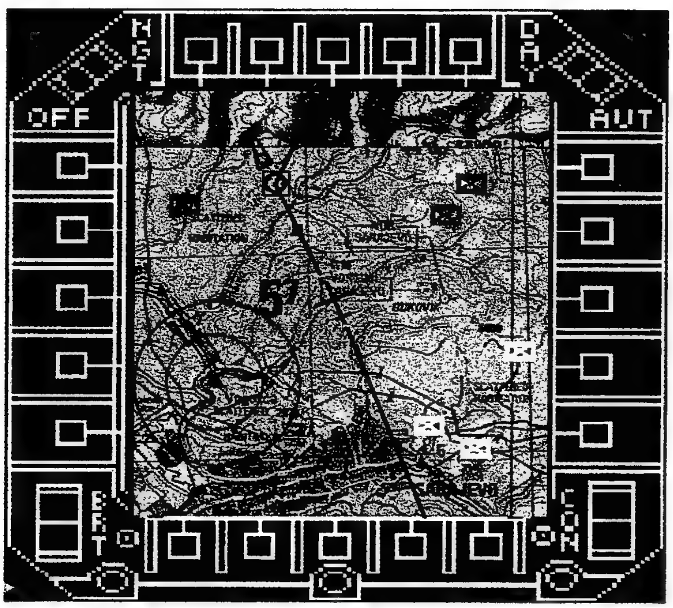

Figure 1. Current 2-D Map Capabilities. Example illustrates map data over Sarajevo and includes tactical overlays.

Table 2. 3-D Requirements Based on the JSF Virtual Ground Map Functionality.

Multi-source/spectral data	Threat overlays
Multi-source/resolution elevation	Updated and real-time threat overlays
Geo-located/specific imagery and elevation	Multiple Fields of view
Display of vector products/data	Degrees of Freedom view angle control
Annotations and pointers	Remote and slewable eye point.

Figure 2. 3-D Perspective Capabilities. Example shows unclassified U.S. Geological Survey imagery and elevation data over the Naval Air Station China Lake, CA.

The 2-D information requires extensive interpretation by the user. The 3D information however, provides intuitive graphics in a mission context for a potential strike platform. Additionally, the growth of communications and display techniques provides an opportunity to update the 3D displayed information within the mission timeline, providing expanded sensor data and situational awareness to the user. The intent is to provide Common Battlefield Awareness which provides the user with command, control, and operational data within the mission context.

The utility of this 3D data can be used at various levels of the command infrastructure. As depicted in Figure 3, at the command center levels, mission preview and rehearsal, fusion of intelligence and threat data can be previewed providing enhanced command and control using intuitive displays. Additionally, "what if" scenarios can be evaluated using advanced modeling, simulation, and analysis tools for both mission and campaign level analysis. Tactical information for real-time operations could use data from Global Positioning Satellites, imagery, and Direct Broadcast Systems providing on-board databases fused with off-board resources. Data can also be overlaid and updated via intelligence sources to bring in the latest battlefield situations.

obstructions, mines, and beach assault routes.

Two important principles that should guide future visualization developments are, (1) an emphasis on using real-world photo-imagery and (2) the use of portable, standardized software tools that use standard hardware. Real-World photo-imagery in visualization systems will display data from any perspective, in any desired level of detail; exploit imagery of varying sources, scale, breadth, or resolution from a variety of sensor platforms; and combine the data into a seamless visual scene. This virtual scene should be correlated to real-world coordinates, other data (such as maps and cultural features) and combined to provide a seamless intuitive 3D display.

Military visualization should also exploit commercial imagery sources. The advancements in commercial data collection, present and planned, will make high resolution commercial imagery an affordable and reliable source.

The use of portable standardized software tools will provide an avenue to keep software development costs in check. As standard commercial hardware evolves, it is anticipated that capabilities will continue to increase as costs decrease. The price-performance advantage of this evolution can best be exploited if the software tools employed to develop these visualization systems are also commercially available versus proprietary software.

Summary: Future visualization capabilities for military users must include requirements to provide intuitive two dimensional and three dimensional data within a mission context. As visualization capabilities progress, consistency of battlespace awareness at the various military command levels can and will become a reality. If we exploit the visualization technologies of today, then tomorrow's warrior, at all levels of command, will be able to view the battlespace with consistency of data in an intuitive command environment.

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[1] Plato translated by G.M Grube, Plato's the Republic, (Hackett Pub. Co.; Indianapolis, ID; 400 BC (1974)); Pg. 164.

[2] M. Lohrenz, et.al., TAMMC Digital Map Requirement Study in Support of Advanced Cockpit Moving Map Displays, NRL Formal Report No. 7441-96-9652, (Stennis Space Center; Stennis MS); Pub. Date TBD; Pg. 5.

DISCUSSOR'S NAME: P. Stockel

QUESTION:

What are the issues associated with, and how do you ensure confidence in the provision of near real-time visual information dissemination in conflict situations?

AUTHOR/PRESENTER'S REPLY:

Maintenance of data requires information to support scanners. Integrity of data requires further consideration. Although the human presence and sensors can also have reduced confidence and integrity through deception and counter-measures techniques.

DISCUSSOR'S NAME: J. Wright

QUESTION:

Are you looking into true stereo 3-dimensional viewing as a means of providing more data, or more understandable data to the viewer?

AUTHOR/PRESENTER'S REPLY:

Yes, three dimensional capabilities have been developed. The need to incorporate true stereo is a large question because of the cost in processing hardware, displays, and data storage. Stereo functions can be replicated using dynamic 2-D displays.

DISCUSSOR'S NAME: F. Adagio

QUESTION:

In trying to produce a near real-life visualisation is there not a real risk of enhancing the effectiveness of opposing forces countermeasures by turning the decoy into a synthetic visual fact? What is the protection against this?

AUTHOR/PRESENTER'S REPLY:

CCD presents a critical problem for data resolution. The issue becomes, "How can we determine when data is not current and when will the user's own information become better than other sources. CCD provides a fidelity of information fusion challenge. Additionally, tactics and concept of operation safeguards should account for information gaps and low confidence level data to counter CCD measures.

MODELLING AND SIMULATION OF COMMUNICATION SYSTEMS

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SUMMARY

The design of digital communication systems involves the definition of the system architecture (e.g. network topology, protocols), the design and modelling of the algorithms/behaviour of the system (e.g. signal processing functions), the design of the hardware/software architecture to be employed and finally, implementation of the algorithms on the chosen architecture. During this design lifecycle the performance of the communications system can be evaluated in three ways, the paper will briefly discuss the characteristics of these methods and highlight when computer modelling/simulation is the best and most efficient way forward in order to gain an understanding of a communication system and an estimate of its performance.

The paper will discuss the migration from computer modelling using standard high-level languages such as FORTRAN towards the use of high level design and simulation packages. The paper will show how such a commercially available package was used to model the physical layer of a public air-to-ground telephone system. The paper will also show how the modelling activity was used within the standardisation process and how these new tools allow models to evolve easily introducing more and more detail until it represents a very accurate model of the real system. The paper will also show how subsequently the computer model was used to assist in the implementation and testing phase of the project.

Finally the paper will discuss the concept of rapid prototyping and its advantages and show how such a modelling tool can also be used to produce prototype equipment.

1 INTRODUCTION

The design of digital communication systems involves the definition of the system architecture (e.g. network topology, protocols), the design and modelling of the algorithms/behaviour of the system (e.g. signal processing functions), the design of the hardware/software architecture to be employed and finally, implementation of the algorithms on the chosen architecture. For example the first step in designing a communications network is to define the overall network architecture, the types of protocols that will be needed, the number and location of nodes, capacity requirements, service quality, etc. Overall system performance requirements are determined and these affect the development of the individual subsystems forming the network. Having identified individual subsystems, the designer specifies the algorithms to be used for that subsystem based on a performance/complexity trade-off.

Throughout this system design process, the designer has a variety of tools to aid the design choices which rely on modelling and simulation. This paper addresses recent trends in the modelling and simulation of radio based digital communication systems concentrating on the algorithm/behavioural element of the design process. The paper will also consider the migration of these algorithms onto the hardware/software architecture and its verification.

There are three ways of evaluating the performance of radio communications systems, by mathematical analysis, by computer simulation and by measurement. The characteristics of these techniques can be summarised as follows:-

1) Mathematical analysis offers quick results with a very good insight into what is actually happening within the process being evaluated, for example, it enables you to see the relationship between the various parameters in the system and the effect of the variation of a parameter. However in most cases it is necessary to make many simplifying assumptions to enable the analysis to be carried out. This is inevitably the case when communication is taking place over propagation channels with multipath and fading.

2) Computer simulation is more time consuming than mathematical analysis but it offers the possibility of being more accurate since there is less need to make as many simplifying assumptions. For example a reasonably accurate model of a radio propagation channel with multipath and fading can be incorporated into the computer model. Carrying out simulations enable optimum choices for parameters within the system to be found and the effect of the variation of these parameters can be seen thus increasing the understanding of the system. Also a computer model can incorporate empirical models and measured data of elements within the system such as filters and amplifiers, thereby increasing the realism of the model.

3) Measurement of the equipment/system once built is likely to prove expensive, more time consuming than computer simulation if hardware redesign is required, may provide limited insight to any problems, and any subsequent changes to solve these problems may prove very costly. However it does provide real time operation and the most

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accurate estimate of performance if used in conjunction with a channel simulator or by trialling in the real world environment.

Thus it is frequently the case that computer simulation offers the best and most efficient way forward in order to gain an understanding of a radio communication system and an estimate of its performance. Modelling and simulation studies can be used to investigate system designs, algorithms, and protocols, and thus reduce the risk of implementing designs which do not meet the required performance specification. This is especially the case if they are carried out at an early enough stage of the development process. Hence modelling and simulation studies are a method of reducing risk within the development cycle. This is equally true for issues related to the design of the physical layer and to network issues such as protocols. As well as simulation studies, estimates of the complexity and ease of implementation are also necessary in the early stages of the design cycle.

It should also be noted that it is increasingly common for simulation to be used in the bid evaluation process for large systems to estimate whether candidate solutions will meet performance requirements.

2 MODERN SIMULATION TOOLS

An increasing trend in the field of computer simulation of complex systems of all types (i.e. link level and network models) is away from dedicated programs written in conventional high level languages (e.g. FORTRAN, C, C++) towards the use of high level simulation packages, wherein simulation models are built up from blocks which are usually graphically represented and joined together in a drawing package-like environment. In most of these packages blocks may be constructed from other blocks leading to a hierarchical structure of increasingly more complex functionality. Non-hierarchical (primitive) blocks may be supplied by the package vendor or written by the user in a suitable high level language.

The advantages of such high level packages to builders of simulation models include:

1) The package provides a graphical interface and representation, which is clearer than a conventional source code program, and provides an element of self-documentation.

2) Automatically generated simulation code means that the model builder can concentrate on writing the algorithmic part of the simulation rather than the I/O and control parts of the model, which are often a major part of a conventional source code program.

3) Libraries of standard blocks are usually provided with the package or as supplementary options.

4) The user can create of his own defined blocks.

5) All blocks, both standard and user defined, are reusable across projects.

6) The automatic or semi-automatic progression from the simulation model to target environment.

The overall result of these advantages is that the package should offer a significant saving on development time and costs for the initial modelling task and also for future modifications, as well as producing a better, and more easily used, model for algorithm evaluation and benchmarking. The principal disadvantages which may occur are a reduction in speed of the simulation but this should be acceptably small with a well-designed model using a suitable package, and a dependence on a single package and its cost.

High level packages of this nature are available for a wide range of application areas. The area of suitable application of a package depends on features such as types of data supported, timing issues (synchronous or event-driven), and types of functions supported in the libraries available. Examples include image manipulation (e.g. AVS/Express [1]), network modelling (e.g. BONeS [2] and OPNET [3]) and signal processing packages, the main topic area of this paper. Signal processing packages include SPW [4], RIPPEN [5], Ptolemy [6] (which is also usable as a network modelling tool), COSSAP [7], Simulink[8] and SystemView [9].

Signal processing packages can be used to carry out simulations at different levels within the algorithm/behavioural design phase, from bit-exact models of a part of a system (e.g. a single ASIC), to models of sub-systems (e.g. a decoder for a radio system coping with fading channels), and to models of the complete physical layer of a system including modems, codecs, filters, amplifiers, models of the propagation environment and the effect of various analogue distortions.

The remainder of this paper will show how such a modern simulation package, in this case SPW, has been used through the development lifecycle of a radio communications project and how it can also be used to produce prototype equipment. As well as the above attributes SPW has the following characteristics (some or all of which are common to other signal processing packages):-

1) SPW is supplied with a Signal Calculator (SigCalc) tool which allows signals (often those stored at certain points during a simulation run) to be loaded, viewed and processed in many ways, e.g. added, transformed by an FFT and viewed as a spectrum, filtered etc. Signals from the calculator may also be used as inputs to simulation runs.

2) Additional tools and libraries can be purchased, such as the Filter Design System (FDS) which enables standard and non-standard filters to be constructed and analysed. Other available libraries include HDS (design and optimisation of DSP hardware including fixed point simulation and analysis), Communications (including modulators, demodulators, coding, equalisers etc.), Radar, RF (non-ideal models of some components) and ISL (real time display of signals in various formats).

3) SPW comes with an extensive library of standard blocks (some hierarchical, most primitive). As well as standard arithmetic, logical, timing, conversion, memory/delay,

source/sink and signal generation blocks it includes many filter blocks such as Butterworth and Chebyshev and also adaptive filters such as LMS and RLS. It also provides non-linear blocks such as amplifier models and FFT and other analysis blocks.

4) SPW has a dynamic multirate capability allowing different blocks in a simulation to run at different rates.

5) SPW offers the capability to migrate from the block diagram simulation to execution on fixed/floating point DSPs, microprocessors, supercomputers and multiprocessor architectures. This may be for speeding up the running of simulations or for rapid prototyping (see Section 5).

3 TFTS

The Terrestrial Flight Telephone System (TFTS) is a system of direct radiocommunication with aircraft throughout Europe and was standardised within the RES5 sub-technical committee of the European Telecommunications Standard Institute (ETSI). The system design enables passengers on-board to communicate at all phases of the flight including airport, during the landing and take-off phases and while in the air. This is achieved using a synchronised network of ground stations providing comprehensive service area coverage. The system uses Time Division Multiplex combined with Frequency Division Multiplex for the ground to air link and Time Division Multiple Access for the air to ground link.

One of the major considerations in the system design has been to provide adequate capacity (incorporating high bandwidth efficiency) and growth potential as new technology emerges. Therefore, the voice signals are digitised using a 9.6 kbits/sec speech coder and a gross bit-rate on each carrier of 44.2 kbits/sec provides 4 voice circuits multiplexed in time, to which is added control signalling. The carrier is modulated using a $\pi/4$ shifted differential quadrature phase shift keying modulation ($\pi/4$-DQPSK). Growth potential is available through the use of 4.8 kbits/sec speech coders as these become available.

4 THE USE OF MODELLING IN THE TFTS PROJECT

This section describes the work carried out at the GEC-Marconi Research Centre in developing a simulation model of the physical layer of the TFTS system. This model was used in different ways through the development lifecycle, from the standardisation process within ETSI, during in-house algorithm studies, providing an estimate of the performance of the overall physical layer from transmitter to receiver and finally in the implementation phase.

The initial standardisation activities in RES5 identified a Requirement Specification for various aspects of TFTS and in particular for the physical layer. The first major task within the standards process that involved the model was the choice of modulation scheme. The goal was to identify the optimum scheme for TFTS, given system requirements on spectrum efficiency, performance and complexity.

Firstly, before any simulations could be carried out to find the error rate performance for different modulation schemes, propagation studies were required to identify the likely channel characteristics that would be encountered in different phases of a flight in order to form the channel model in the simulation model of the physical layer of TFTS. Propagation models were required for the three phases of a flight, the in-flight, take-off/landing and the airport phase.

The in-flight model was based on a time varying Doppler shift of the modulated signal carrier due to the motion of the aircraft. By selecting the initial conditions of the model (i.e. aircraft speed, height and distance) various scenarios can be simulated such as maximum Doppler shift (i.e. when the aircraft is at maximum range) or maximum rate of change of Doppler shift (i.e. when the aircraft flies over the basestation).

The take-off/landing and airport phases are characterised by fading channels. The fading channel model employed within the simulator is based on a classical Rayleigh fading channel having power spectral density:

$$S(f) = \begin{cases} \dfrac{1}{\pi f_d \sqrt{1 - \dfrac{f^2}{f_d^2}}} & -f_d < f < f_d \\ 0 & \text{otherwise} \end{cases}$$

where $f_d = v/\lambda$ is the maximum Doppler shift
v = aircraft speed,
and λ = wavelength.

A general Rician fading model (i.e. the sum of direct and Rayleigh fading components) was also used where the direct component is subject to either a constant or time-varying Doppler shift. The take-off/landing scenario was modelled using a single Rician fading channel, whereas the airport scenario was modelled with a Rayleigh fading multipath channel containing up to 6 paths of varying delay and power.

Other scenarios were readily simulated using a combination of the base elements (i.e. fading, both Rayleigh and Rician, multipath and Doppler shift) with appropriate parameters chosen for each.

The model was used to compare the three candidate modulation schemes, Gaussian minimum shift keying (GMSK), offset quadrature phase shift keying (OQPSK) and $\pi/4$-DQPSK. Simulations over the various channel models were carried out using models of ideal modulators and demodulators and the results input to the ETSI RES5 Committee. These results along with comparisons of spectral efficiency and complexity were then used to determine that $\pi/4$-DQPSK was the best choice for the modulation scheme for TFTS since by comparison GMSK suffers from lower spectral efficiency and the OQPSK performance suffered in the fading environment using simple receiver designs.

The model at this stage was relatively idealised with few system distortions included. In order to increase the realism of

the model and thus increase confidence in the results produced, the model was updated by including the effects of implementation imperfections and analogue equipment. In addition to the channel model already described, the simulation model included the following elements as shown in Figure 1 and an error rate analysis block. These various elements are now briefly described:

Modulator

The block diagram of the modulator is shown in Figure 2. The input data is split into I and Q channels by a serial to parallel convertor. The differential encoder converts the I/Q dibit pair such that the phase advance of the signal is given by:

I	Q	Phase advance of modulated signal
1	1	$\pi/4$
0	1	$3\pi/4$
0	0	$-3\pi/4$
1	0	$-\pi/4$

RC(β) in Figure 2 represents a Nyquist bandwidth square root raised cosine filter with a roll-off factor β. In this case the square root raised cosine filtering was approximated by an FIR filter designed using an equiripple design program allowing arbitrary frequency response. The input to the modulator block is random data bits having the timeslot and frame structure of the TFTS system.

TX Analogue Distortion

The four key elements of analogue distortion included within the simulation model were digital to analogue (D-A) conversion, analogue filtering, phase noise and power amplifier (PA) distortions. The analogue filter distortion was incorporated to model the low-pass anti-aliasing filter following the D-A convertor and a band-pass mixing filter prior to the PA.

RX Analogue Distortion

Two elements of analogue distortion considered for inclusion within the simulator were analogue filtering and analogue to digital (A-D) converter distortion. The analogue filtering was not included due to the relative wideband nature of the analogue filters compared to the digital receive filters and their flat response over the signal bandwidth. The A-D distortion was included as part of the demodulator model.

Demodulator

The demodulator was based on a baseband differentially detected $\pi/4$-DQPSK scheme as shown in Figure 3. The 'SYNC' block provides initial synchronisation, bit timing and Doppler frequency tracking. The algorithms employed within the demodulator are equivalent to those used within the hardware implementation, with all operating parameters being derived from the received signal. As for the modulator, the FIR filter approximating the square root raised cosine filter was designed using an equiripple design program and the combined effect of the transmit and receive digital filters was to approximate the Nyquist bandwidth raised cosine filter.

Error Rate Analysis

Error rate analysis was performed using Monte-Carlo simulation and counting the number of errors between the transmitted data-bits and those demodulated by the receiver. In this case only the data-bits within a general data timeslot were processed, the guard, correlation and synchronisation bits being ignored. In addition to error rate and error rate variance estimation, the distribution of errors within a block of signal was also analysed.

Simulation Results

This section describes some typical results that were obtained from the simulation model. In this case the model was configured for continuous transmission of general data time slots (i.e. ground to air), with typical system parameters.

The bit-error performance under static, in-flight (maximum Doppler shift = 1500 Hz), take-off/landing (fade rate = 320 Hz) and airport (fade rate = 53 Hz) phases are shown in Figure 4. As can be seen the typical irreducible error rate associated with fading channels is evident. The degradation in performance for the in-flight scenario is mainly due to the receive filters being offset from the Doppler shifted carrier. However, the result does demonstrate the ability of the algorithms to track the changing Doppler shift. In addition to bit-error performance measures, the model was used to generate measures of spectrum occupancy, received vector error and signal quality.

Simulation results like those above became the basis for performance requirements for the TFTS physical layer and as such were incorporated into the ETSI TFTS physical layer specification. This is normal practice in civil standards; simulation results are used as the conformance specifications (modified by a permitted implementation factor) that radio equipment must meet before being allowed on air (e.g. GSM, DCS1800 and TETRA).

Implementation Phase

Once the TFTS system specification had been standardised, the GEC-Marconi Research Centre (GMRC) worked closely with GEC-Marconi Sensors to develop products based on TFTS. Most of our work concentrated on the physical layer performance and included replacing some of the distortion models by measurements of elements to be used in the production equipment. Thus, for example, the power amplifier model characteristic was replaced in the model by measurements of the actual power amplifier module to be used in the real equipment. Thus the results of simulations more and more closely approximated the performance that would be achieved from the prototype equipment. At the end of this simulation stage the model closely represented the actual implementation of the physical layer equipment being developed by GEC-Marconi Sensors.

Having developed the model for the uses described above it was then used to assist in the implementation phase of the TFTS project in a number of ways. Firstly, having specified an algorithm/function, such as the modulator, and having produced the DSP code for the algorithm/function, the code was verified against the SPW model by passing the same test vectors through the model and the DSP code. Functionally equivalent DSP code will produce the same output as the model except for factors introduced by the difference in precision between the model and the DSP.

Secondly, implemented elements within the system such as the modulator and demodulator were tested against the model. For example, for the hardware demodulator, the simulation model was run to produce a file of demodulator input signals which was then passed into the hardware demodulator via a dual arbitrary waveform generator (DAWG). The output of the hardware demodulator was then compared to the simulation demodulator output. Again because of the detail included in the model the results should be comparable apart from differences in the precision of the hardware and the model. This greatly helped in debugging the hardware elements of the system.

Finally as shown in Figure 5 the complete physical layer implementation was tested and evaluated by using the simulation model to generate the fading channels only. The results generated by the hardware system was then compared with the output of equivalent simulation runs. In this case Figure 6 shows such a result and this gave confidence in the hardware solution before moving to a production phase.

5 RAPID PROTOTYPING

The implementation phase of the TFTS project relied on an algorithm specification of the physical layer subsystem which was converted into the chosen hardware/software architecture. The model was only used in the verification of the implementation. Although the computer model was a good representation of the implementation the target hardware had to be developed prior to the final algorithm verification phase.

Rapid prototyping is the verification of embedded DSP systems using prototype hardware (usually based on the product target hardware) in an efficient and seamless manner from an algorithmic description of the system. It allows real-time performance evaluation of algorithms/systems on target processors, and a performance evaluation under real operating conditions. From a product development viewpoint carrying out rapid prototyping offers the following advantages:

1) It enables a functionally correct hardware system to be developed quickly.

2) It highlights algorithm/system problems before any costly product development.

3) It increases customer confidence in the algorithms/system solution by showing whether it meets performance requirements under real operating conditions.

4) It thereby reduces risk in the product development cycle.

Along with many other modern signal processing simulation tools SPW offers the capability of automatic or semi-automatic progression from simulation model to code suitable for various floating point DSPs. This allows models and modifications to models to be made and tested in SPW, and then quickly ported and tested in a prototype system whereas previously it would have been a more expensive exercise to make changes to the hardware/software components.

SPW offers the capability of producing a stand-alone C program of the simulation model via the optional Code Generation System (CGS) package for standard C implementation. This may then be compiled and run on the same workstation, another platform or on a target processor (or processors) using a suitable compiler. The CGS option produces reasonably efficient source code and the main source of inefficiency in this route is the compiler.

As alternatives to the CGS standard C option there are other CGS options available for specific processors such as the TI TMS32C40 and C30, AT&T DCP32C and Motorola DSP96002 processors. In addition a porting kit package allows porting of code to any suitable DSP. This will produce a more efficient route to DSP code than the standard C route due to the use of DSP specific optimised run-time libraries.

To port a modelled system to a multiple processor system requires, for maximum efficiency and minimum effort, a further additional package called Multiprox. This may be used to partition the simulation model for execution on two or more processors. It works with CGS to generate code for each processor including the code necessary for efficient communication between processors. To prepare a design for partitioning the user simply selects one or more blocks in an SPW diagram and enters the name of the processor dedicated to those blocks (without modifying the SPW model). As well as UNIX based hosts, Multiprox supports standard multiprocessor DSP development boards.

At the GEC-Marconi Research Centre we have been carrying out an experiment into the feasibility of rapid prototyping from an SPW model onto a high performance large capacity DSP system. The approach taken has been to design and build a model in SPW and then to port the code to a high performance real-time floating point DSP system optimised for large scale signal processing tasks developed at G-MRC, Figure 7.

This 'GFLOPS' system is based on a multiprocessor module containing five Motorola DSP96002 devices that is capable of 300 MFLOPS. System size can be scaled from 300 MFLOPS to 25 GFLOPS. The system is designed as an integrated real-time processor with multiple analogue input and output channels. Each processor module has 16 analogue input channels and 8 analogue output channels all with 14 bit resolution and sampling up to 100kHz. Software support provides a library of parallel functions to perform FIR/IIR filtering, matrix and vector arithmetic efficiently. Floating point calculations can be distributed in parallel over four of the processors. This technology has been well proven in large systems (up to 10 GFLOPS) and small scale systems are ideal for rapid prototyping and proof-of-concept demonstrators.

The example chosen for the rapid prototyping experiment was an enhanced and flexible prototype HF channel simulator which apart from being a suitable test for the methodology would also provide us with a very useful application tool. The channel simulator model is based on the current ITU-R Recommendations and Reports [10,11,12] which we have as coded blocks in our current in-house SPW library. Further objectives are to provide the user with a graphical user interface (GUI), and a display of the channel activity function. The final system will use an HF ionospheric propagation model to calculate the channel simulator path parameters for

typical and extreme path scenarios e.g. path delays, signal-to-noise ratios, etc.

The prototype simulator will digitise the input baseband analogue signal, perform the discrete path and channel signal processing, and then convert the signal to analogue form on exit. The maximum nominal baseband bandwidth will be 5000Hz. The simulator will be capable of handling at least 2 independent channels with each channel having a maximum of 5 paths. The tests stated in [10] will be used as a benchmark for the implementation, however a future enhancement will enable each path to have tuneable parameters. The proposed implementation will have tuneable channel parameters with the following ranges:-

Frequency shift (Hz):	-500	to	+500
Path attenuation (dB):	0	to	60
Frequency spread (Hz):	0	to	100
Path delay (ms):	0	to	20

To avoid aliasing, the analogue-to-digital conversion requires a sampling rate in excess of 4 times the audio bandwidth. Hence the desired sampling rate should be >20kHz.

The core of the simulator is an SPW implementation of the channel model. The model is composed of a number of SPW blocks which are linked together through which the signal passes. At present a single channel model has been implemented. Further channels can be added by replication of the existing single channel model. Each channel comprises a number of paths. At present, the frequency spread for each path is identical, with the frequency shift, the path attenuation and the path delay tuneable. The current implementation uses a stationary Gaussian-scatter model for the channel with the individual paths being 'tapped-off' at the appropriate delay intervals. At each tap, the delayed signal is modulated in amplitude and phase by the tap-gain function. The delayed and modulated signals are summed with additive noise to form the output signal. In [12] which describes the model, each tap-gain function is the sum of two independent complex Gaussian random processes (representing the two magnetoionic components) with zero mean values and independent real and imaginary components with equal r.m.s. values that produce Rayleigh fading. The full model requires frequency shifts (Doppler shifts), the attenuations and the frequency spread for each magnetoionic component. In our implementation the Doppler shifts, the attenuation factors and the tapped delay line parameters (i.e. the propagation delay between modes) are set independently. All paths have the same frequency spread.

The Rayleigh fading path is calculated by passing complex white Gaussian noise (WGN) samples through a spectrum shaping filter whose characteristic produces the required Rayleigh fading. At present two spectrum shaping filters are available: a "classical" Rayleigh fading characteristic and a Gaussian characteristic [12]. The bandwidth of these shaping filters control the frequency spread of the path. Because the frequency spread is usually much less than the sampling frequency, the spectrum shaping filter is usually a very narrow lowpass filter. Therefore, in order to minimise the computational load, the output of the spectrum shaping filter is interpolated from a lower sampling frequency. The interpolated output of the spectrum shaping filter is used as the tap gain function. Each path has an independently generated tap gain function. A Gaussian random number generator is used to produce a noise component which is added to the sum of the individual path components in the channel prior to output.

The final HF simulator is expected to have 2 channels and 5 paths per channel. This implementation will require considerable amounts of processing power if the sampling rate is 20kHz. Therefore the channel simulator code will be distributed over 4 processors and so it will enable the path fading calculations to be performed between samples. Hence a simple single-channel single path model is currently being implemented so that timing information can be gathered for each major calculation block within the simulator. This data will then be used to partition the code into 4, approximately equal, processing blocks. The timing will also enable the scaling to be made from one-channel one path to multiple-channels and multiple-paths. Because the present DSP card has a fixed limit in terms of processing size, it will be possible to calculate the upper limit of the number of channels and number of paths which can be processed at 20kHz using a single 'GFLOPS' card. Having determined the number of channels and paths that can be achieved with a single 'GFLOPS' card, an SPW model with the appropriate number of channels and paths will be constructed. The CGS will then convert the SPW model into suitable partitioned 'C' code for the DSPs.

A GUI has been developed to allow input simulation parameter changing, the download of the simulator software to the DSP hardware and the resultant control of the software using the set parameters. The GUI provides data validation of the simulation parameters together with the ability to save and restore standard channel scenarios from data files. An additional feature will also include a graphical display of the tap gain function of each path, both instantaneous and long-term average. The GUI is designed in such a way as to separate the DSP hardware and software control functions from the main interactive input functions with the DSP hardware and software configurations being read from initialisation files. In this way the DSP control functions can be used for any such prototype system.

The HF simulator project has demonstrated that the concept of rapid prototyping using a high-level graphical package such as SPW is feasible. Work is now concentrating on the design of the final HF simulator, based on the single channel/single path timing analysis, and an investigation into the efficiency of the run-time libraries supporting the rapid prototyping methodology.

Virtual prototyping is an extension of rapid prototyping where the prototype hardware is itself virtual and usually contained within the design environment. The virtual model of the implementation environment can either be based on a complete model of the target hardware or on the use of co-simulation whereby DSP code is executed using instruction set simulators and hardware descriptions are run on an HDL simulator with the necessary timing and data passing functions controlled by the virtual prototype environment. Virtual prototyping allows verification of the hardware and software architectures as their design gets mapped into implementation.

Once the design engineer is satisfied with the final hardware/software implementation, the design can be committed to implementation.

6 CONCLUSION

This paper has shown how modelling and simulation using a modern software simulation package offered great benefits in the development lifecycle of a radio project from initial standardisation activities to the implementation phase. The feasibility of using such a package to produce prototype equipment has also been demonstrated offering the potential of reducing risk in the development lifecycle.

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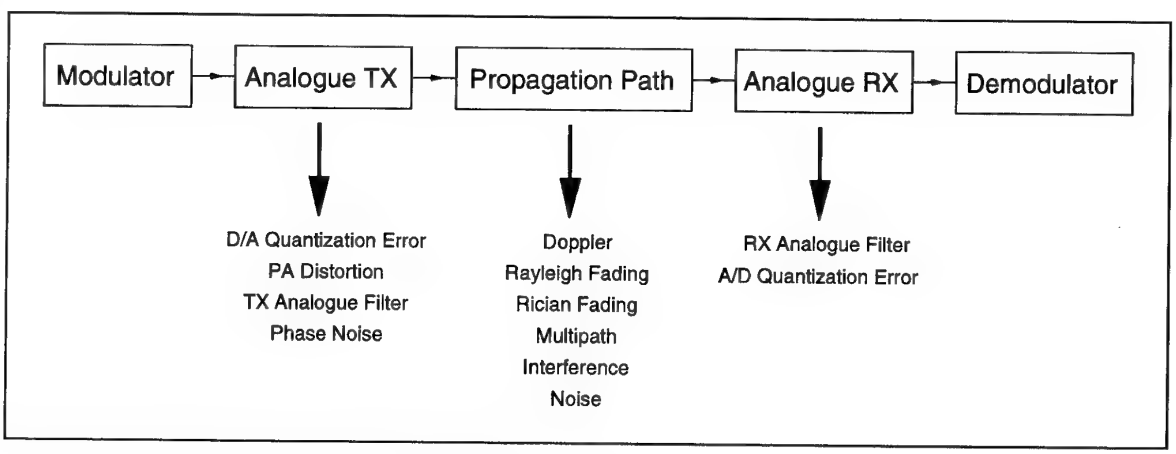

Figure 1. TFTS Simulation Block Diagram

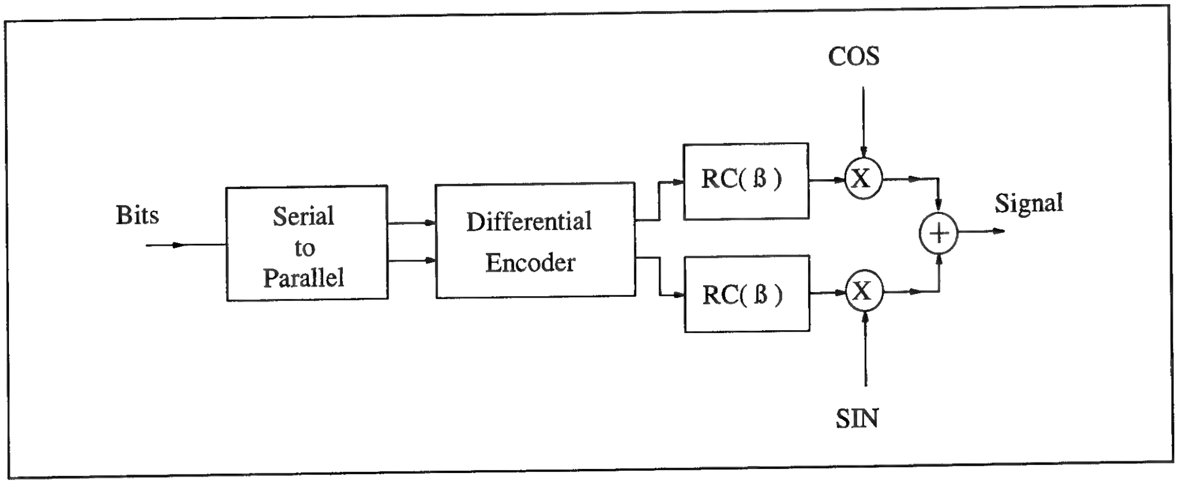

Figure 2. TFTS Modulator Block Diagram

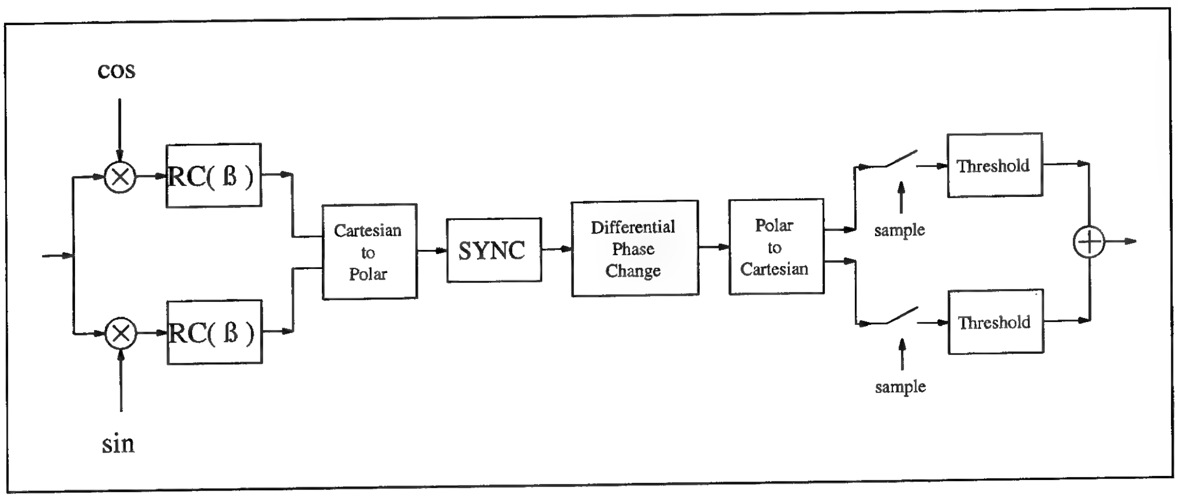

Figure 3. TFTS Demodulator Block Diagram

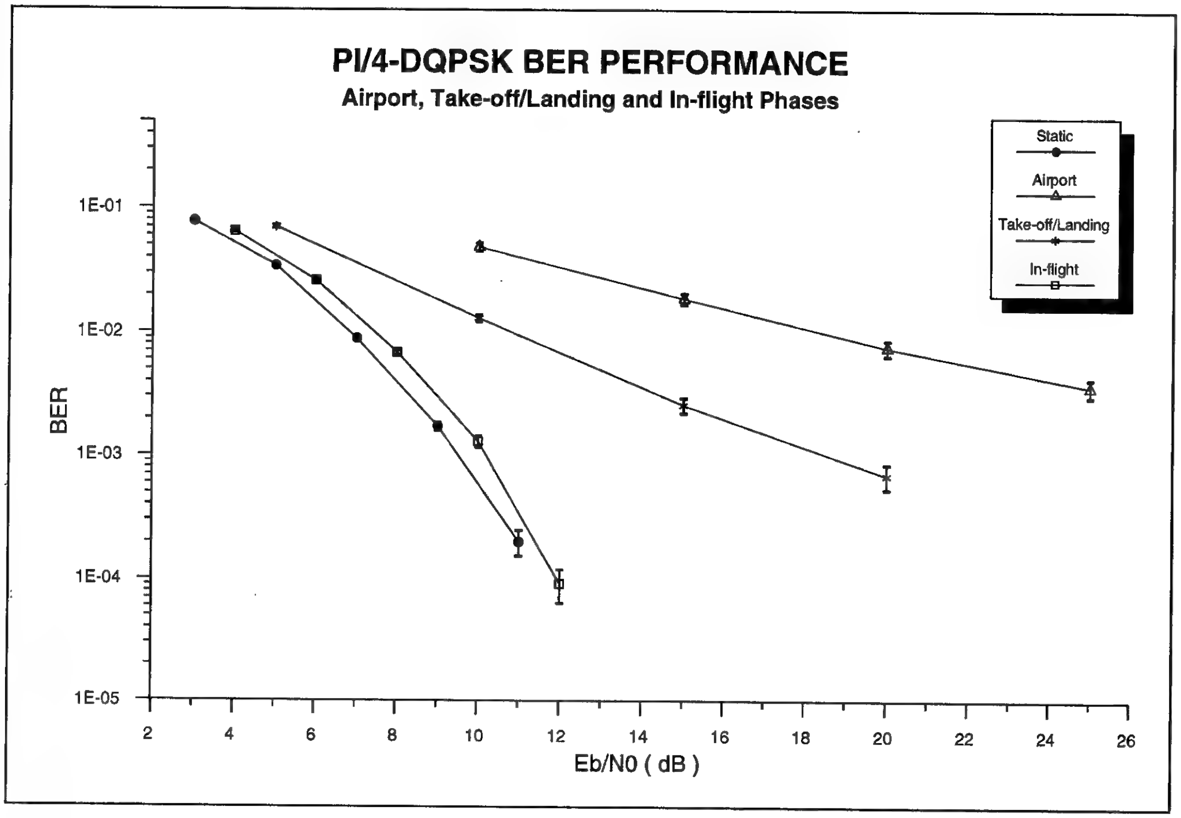

Figure 4. TFTS Bit-error Performance Results

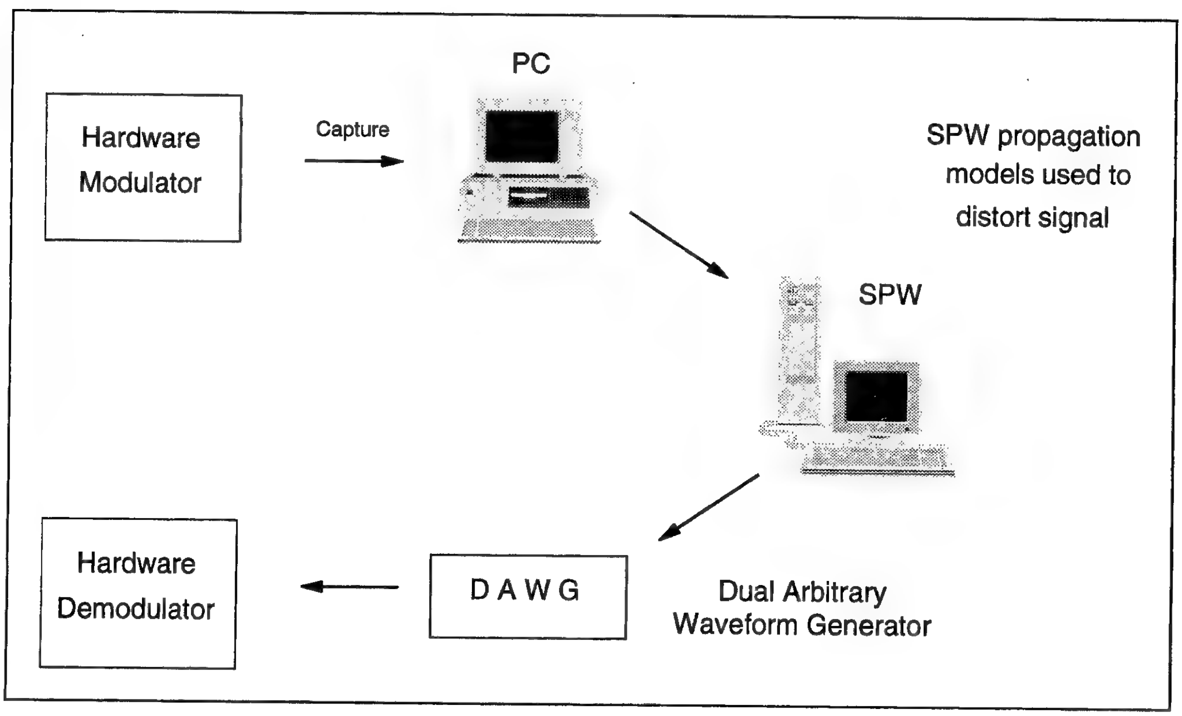

Figure 5. Testing the Physical Layer Implementation

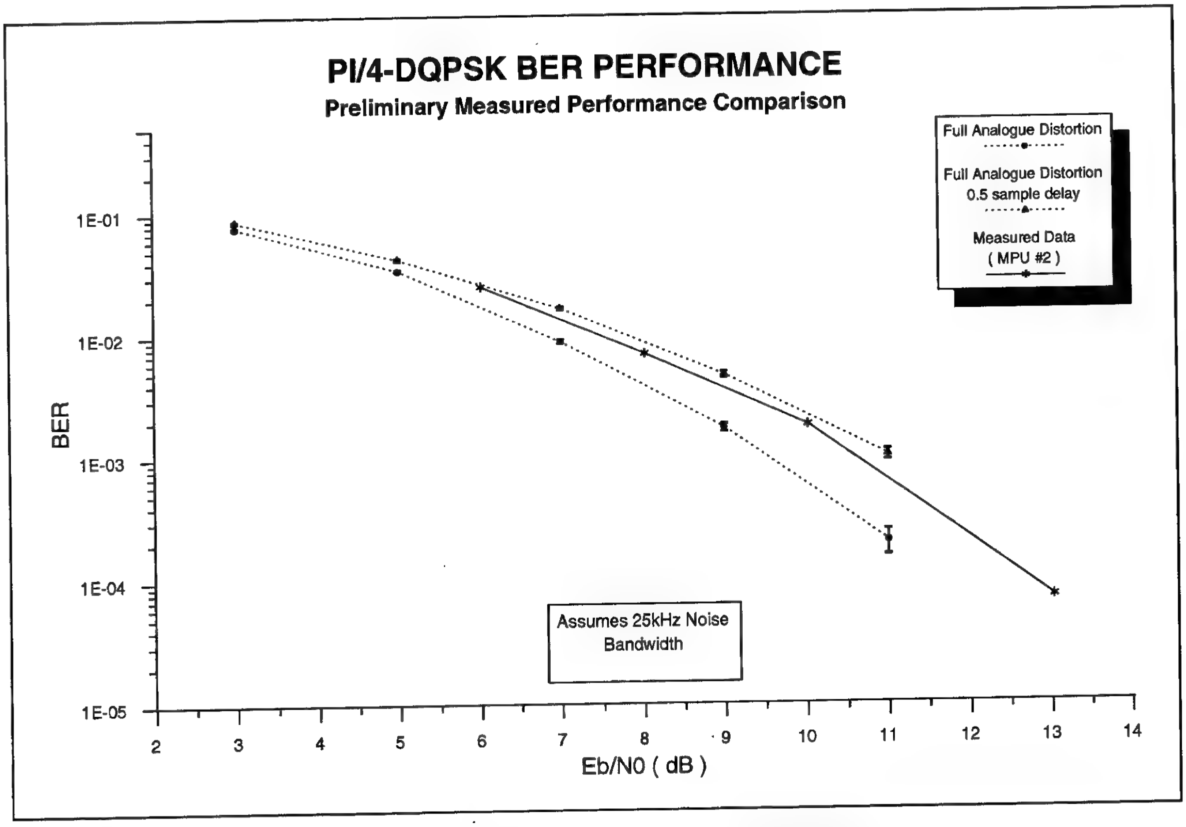

Figure 6. Comparison of Model and Implementation Results

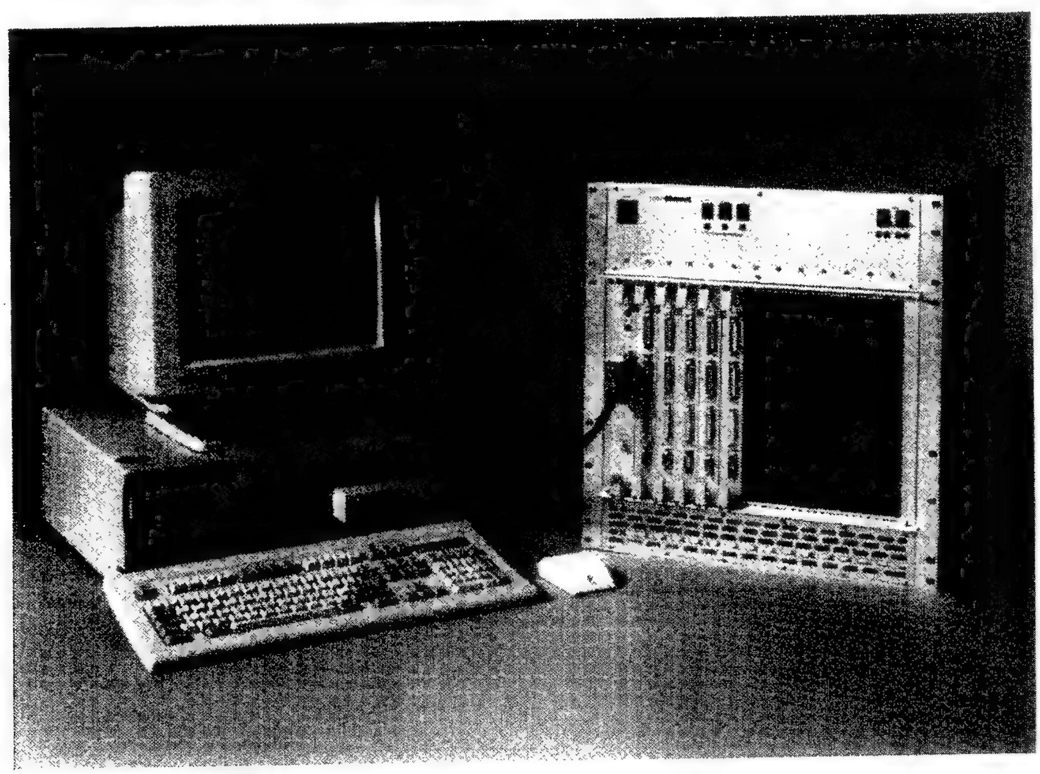

Figure 7. GFLOPS DSP System

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Synthetic aperture radar	Military communication	Mathematical models
UWB (ultra wideband) technology	Telecommunication	Environments
		Reviews

14. Abstract

One of three volumes containing the unclassified papers presented at a conference on "Future Aerospace Technology in the Service of the Alliance" organised by AGARD (NATO's Advisory Group for Aerospace Research and Development) at Palaiseau, near Paris, France, 14-17 April 1997. The conference took the form of three parallel symposia and three plenary sessions.

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